

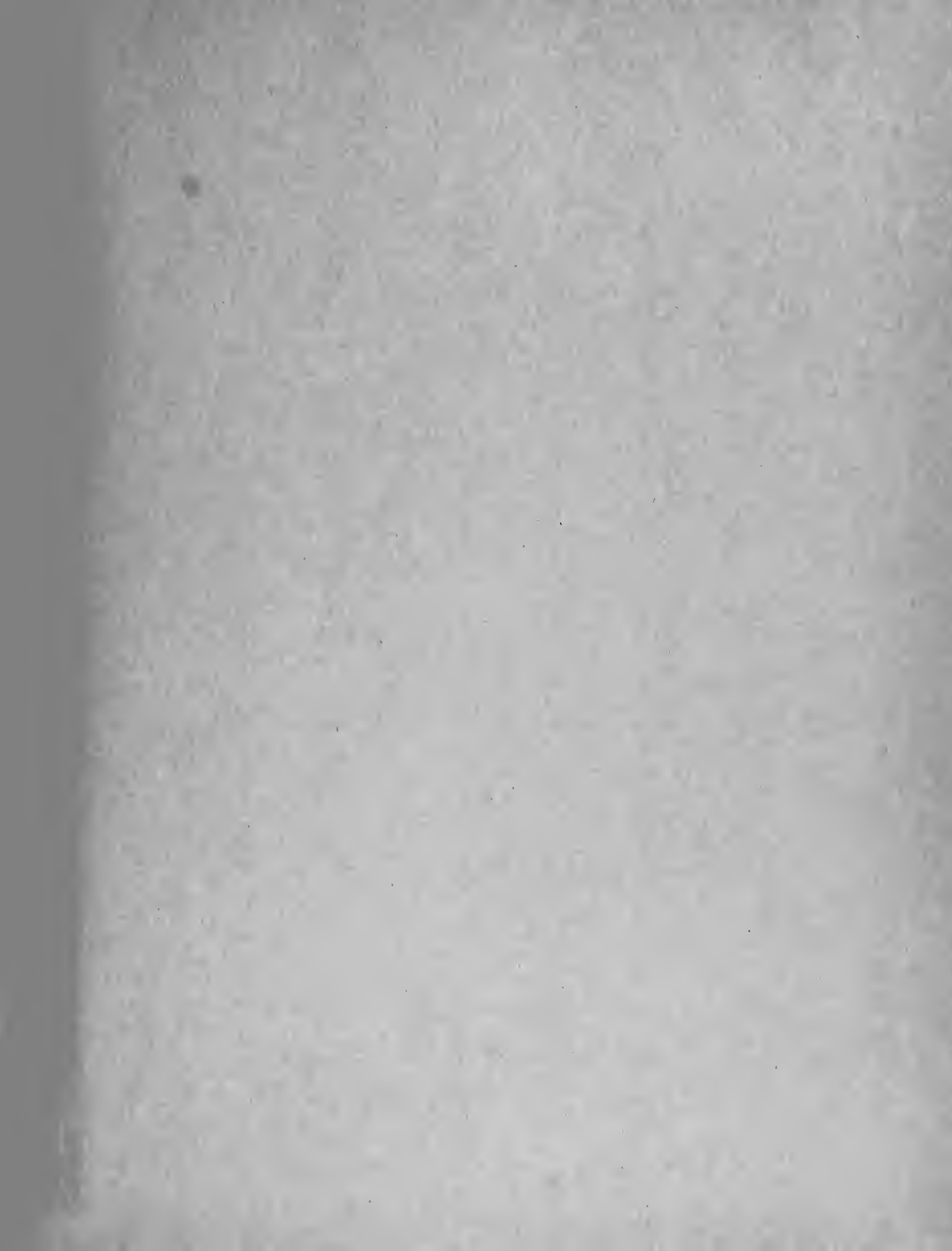
THEORETICAL INVESTIGATIONS  
OF THE  
RESISTIVITY - SATURATION  
RELATIONSHIP IN POROUS  
MATERIAL

BY  
FRANK JOHN REH

Thesis  
R32

THESIS  
R32

Library  
U. S. Naval Postgraduate School  
Monterey, Md.









**Theoretical Investigations of the  
Resistivity-Saturation Relationship in Porous Material**

**By**

**Frank John Reh**

**B.S. (United States Naval Academy) 1942**

**THESIS**

**Submitted in partial satisfaction of the requirements for the degree of**

**MASTER OF SCIENCE**

**in**

**Petroleum Engineering**

**in the**

**GRADUATE DIVISION**

**of the**

**UNIVERSITY OF CALIFORNIA**

**Approved:**

..... O. J. M. Smith .....

..... W. H. Somerton .....

..... J. A. Putnam .....

**Committee in Charge**

**Deposited in the University Library..... June 15, 1950 .....**

**Date**

**Librarian**





**Theoretical Investigations of the  
Resistivity-Saturation Relationship in Porous Material**

**By**

**Frank John Reh**

**B.S. (United States Naval Academy) 1942**

**THESIS**

**Submitted in partial satisfaction of the requirements for the degree of**

**MASTER OF SCIENCE**

**in**

**Petroleum Engineering**

**in the**

**GRADUATE DIVISION**

**of the**

**UNIVERSITY OF CALIFORNIA**

Thesis

R32

May 15, 1950

Berkeley, California.

The Faculty of the Department of Engineering,  
University of California,  
Berkeley, 4, California.

Gentlemen,

In accordance with the regulations of the Graduate Division of the University of California, I submit herewith a thesis entitled "Theoretical Investigations of the Resistivity-Saturation Relationship in Porous Materials".

This is in partial satisfaction of the requirements for the Degree of Master of Science with specialization in Petroleum Engineering at the University of California.

THE UNIVERSITY OF CALIFORNIA  
BERKELEY, CALIFORNIA

The Faculty of the Department of Anthropology,  
University of California,  
Berkeley, 4, California.

Gentlemen,

In accordance with the regulations of the Graduate Division  
of the University of California, I hereby certify that  
"Theoretical Anthropology" of the Department of Anthropology  
in honor of the late Professor H. H. Henshaw,  
this is to certify that the following named persons  
Degrees of Master of Arts in Anthropology have been conferred  
of the University of California.

Very truly yours,

#### ACKNOWLEDGEMENT

The writer wishes to acknowledge the assistance received from many sources in the completion of this work.

Initially it is desired to acknowledge the indebtedness to the United States Naval Service for placing the writer in a position where such a study was possible. It is to be noted, however, that the ideas and opinions expressed herein are those of the author and do not necessarily represent those of the Navy Department of Naval Service.

The advice, criticisms, and many helpful suggestions given by the committee in charge of this work, Professor W. H. Somerton, Professor J. A. Putnam, and Professor O. J. M. Smith, were invaluable.

Finally the help given by R. W. Voss, R. W. Ravenscroft, and S. P. Miller in the many ideas they presented, did much to help clarify many detailed aspects of the analysis.

ADMINISTRATIVE

The author wishes to acknowledge the assistance received

from many sources in the completion of this work.

Initially it is desired to acknowledge the indebtedness

to the United States Navy for placing the writer in a position

where much a study was possible. It is to be noted, however, that the

ideas and opinions expressed herein are those of the writer and do not

necessarily represent those of the Navy Department or Naval Air Force.

The review, criticism, and many helpful suggestions given

by the committee in charge of this work, Professor G. H. Compton,

Professor J. J. Thomson, and Professor J. J. Van Allen, were invaluable.

Finally, the help given by J. J. Van Allen, J. J. Thomson, and

S. P. Winter in the early stages of this work, and also the help of many

many other individuals in the analysis.

# THEORETICAL INVESTIGATIONS OF THE RESISTIVITY-SATURATION RELATIONSHIPS IN POROUS MATERIALS

## ABSTRACT

In this paper it has been shown that the similarity existing between electrical and hydraulic flow leads to a relationship between electrical conductivity and hydraulic permeability. Expressed in terms of relative resistivity and relative permeability to the wetting phase, the relative permeability is equal to the relative resistivity times the square of the conducting fluid saturation.

Analysis of the data of previous investigators shows that for clean unconsolidated sands the relative permeability is equal to the square of the relative resistivity. For consolidated sands the data are not as definitive, but the indications are that the relative permeability will be less than the square of the relative resistivity.

## INTRODUCTION

Since the time of its inception the electrical log has been used primarily to correlate structures and geology in local areas, and to indicate qualitatively a given stratum's fluid content. It is readily apparent that quantitative relationships between fluid content and the data available from the electric log would increase the value of the latter many times.

The problem here is two-fold. There must be established a quantitative relationships between the brine saturation of a porous matrix and its resistivity at this saturation. Further, the relationship of the

ABSTRACT

In this paper it has been shown that the fundamental laws of electricity and magnetism can be derived from a few simple principles. The first of these is the principle of the conservation of electric charge, which states that the total charge in a closed system is constant. The second is the principle of the conservation of magnetic flux, which states that the total magnetic flux in a closed system is constant. The third is the principle of the conservation of energy, which states that the total energy in a closed system is constant. The fourth is the principle of the conservation of momentum, which states that the total momentum in a closed system is constant. The fifth is the principle of the conservation of angular momentum, which states that the total angular momentum in a closed system is constant. The sixth is the principle of the conservation of mass, which states that the total mass in a closed system is constant. The seventh is the principle of the conservation of information, which states that the total information in a closed system is constant. The eighth is the principle of the conservation of entropy, which states that the total entropy in a closed system is constant. The ninth is the principle of the conservation of the speed of light, which states that the speed of light is constant in all inertial frames. The tenth is the principle of the conservation of the laws of physics, which states that the laws of physics are the same in all inertial frames. These ten principles are the foundation of the theory of electricity and magnetism.

INTRODUCTION

The theory of electricity and magnetism is one of the most important and successful theories in physics. It has been developed over a long period of time, from the early work of ancient philosophers to the modern work of physicists. The theory is based on a few simple principles, which are the foundation of the theory. These principles are the conservation of electric charge, the conservation of magnetic flux, the conservation of energy, the conservation of momentum, the conservation of angular momentum, the conservation of mass, the conservation of information, the conservation of entropy, the conservation of the speed of light, and the conservation of the laws of physics. These principles are the foundation of the theory of electricity and magnetism. The theory has been used to explain a wide range of phenomena, from the behavior of individual particles to the behavior of large-scale systems. The theory has also been used to develop new technologies, such as the electric motor and the radio. The theory is one of the most important and successful theories in physics.



true resistivity to that obtained with the log, complicated as it is by many side effects, must be established. This problem is being studied primarily by the oil well servicing companies, and although the answer is not complete, satisfactory empirical relationships have been worked out in the form of curves. (1) The problem of the quantitative saturation-resistivity relationship, with which this paper will concern itself, has been primarily one of the laboratory and has been attacked by many investigators. (2)(3)(4)(5)(6)(7)

The first definitive work to extend the usefulness of the electrical log in a quantitative sense was done by Archie. (2) He proposed a method for determining the oil or water saturation of a reservoir bed from a measure of its resistivity as compared to the resistivity of the brine with which it was partially saturated.

From an extensive series of data Archie postulated two empirical relations:

$$F = f^{-m} \quad (1)$$

$$S = (R_o/R)^{1/n} = (FR_w/R)^{1/n} \quad (2)$$

where  $F$  is a "formation resistivity factor" defined as the resistivity of the saturated matrix ( $R_o$ ) divided by the resistivity of the brine with which it is saturated ( $R_w$ )  
 $f$  is the fractional porosity,  
 $m$  is an exponent termed the cementation factor,  
 $S$  is the fractional brine saturation,  
 $R$  is the resistivity of the partially saturated matrix, and  
 $n$  is the saturation exponent, usually taken as 2.

This work opened the field for subsequent investigators to establish a more precise relationship between the brine saturation of a porous matrix and the resultant resistivity. In the main these efforts have been directed



toward establishing a value for "n" that will result in more consistently correct evaluation of the saturation, and toward showing that the resistivity is a function of the method of saturation and of the fluid distribution.

Certainly studies of the variation of resistivity with distribution are very necessary since the distribution of the fluids will probably effect the resistivity. When the medium is wet by the conducting phase the effect is usually small, but marked variations have been shown to occur in some cases when the sand is oil wet.<sup>(8)</sup>

However, it must be remembered that the data obtained have been applied to an expression which was put forth initially as an approximate relationship without a solid theoretical justification. To overcome this difficulty, the problem was attacked from a fundamental theoretical standpoint. Idealized pore spaces were broken up into incremental elements and the resistivity relationships were analyzed. By this means the relationship between resistivity and saturation was determined for simple idealized pore spaces.

This approach to the problem showed that even in these simple cases the relationships were very complex, and that no simple, general solution of the relationship was available from the geometry of the system alone. Another independent parameter was required. The relationships obtained and their derivations are contained in Appendix I.

#### CONCEPT OF RELATIVE RESISTIVITY

If the laws of electrical flow are considered, it will be noted

1. The first part of the report deals with the general situation of the country.

2. The second part of the report deals with the economic situation of the country.

3. The third part of the report deals with the social situation of the country.

4. The fourth part of the report deals with the political situation of the country.

5. The fifth part of the report deals with the cultural situation of the country.

6. The sixth part of the report deals with the environmental situation of the country.

7. The seventh part of the report deals with the international situation of the country.

8. The eighth part of the report deals with the future prospects of the country.

9. The ninth part of the report deals with the conclusion of the report.

10. The tenth part of the report deals with the annexes of the report.

11. The eleventh part of the report deals with the bibliography of the report.

12. The twelfth part of the report deals with the index of the report.

13. The thirteenth part of the report deals with the list of figures of the report.

14. The fourteenth part of the report deals with the list of tables of the report.

15. The fifteenth part of the report deals with the list of abbreviations of the report.

16. The sixteenth part of the report deals with the list of symbols of the report.

17. The seventeenth part of the report deals with the list of units of the report.

18. The eighteenth part of the report deals with the list of references of the report.

19. The nineteenth part of the report deals with the list of sources of the report.

20. The twentieth part of the report deals with the list of authors of the report.

21. The twenty-first part of the report deals with the list of titles of the report.

22. The twenty-second part of the report deals with the list of subjects of the report.

23. The twenty-third part of the report deals with the list of keywords of the report.

24. The twenty-fourth part of the report deals with the list of terms of the report.

25. The twenty-fifth part of the report deals with the list of definitions of the report.

that for a constant electrical voltage and resistivity the amount of current flow per unit of length will be a function of the area available to flow. For hydraulic flow through a capillary tube, for a constant pressure gradient, the rate of fluid flow will be proportional to the radius of the tube raised to the fourth power. This was indicated by Wyllie and Rose<sup>(9)</sup> when they called attention to "a fundamental difference between viscous resistivity to fluid flow and electrical resistivity. The former effect depends principally on the pore radius to the fourth power ( $r^4$ ) and the latter to (sic) the radius squared ( $r^2$ )".

With this concept in mind the relationship between electrical conductivity and hydraulic permeability will be developed as follows:

Consider a porous matrix saturated with a brine of resistivity  $R_w$ . The resistance offered to electrical flow is given by the relation

$$R_{es} = (d/na)R_w \quad (3)$$

where  $d$  is the average length of the pore channels,

$n$  is the number of pore channels, and

$a$  is the average cross sectional area of the pores.

The resistivity of the saturated matrix,  $R_o$ , is given by

$$R_o = R_w(d/na)(A/L) = (d/L)(A/na)R_w \quad (4)$$

where  $L$  is the length of the matrix in the direction of electrical flow, and

$A$  is the cross sectional area of the matrix.

If the fractional porosity,  $f$ , is written in terms of the geometry of the system

$$f = \frac{\text{void volume}}{\text{bulk volume}} = \frac{(d)(na)}{(L)(A)} \quad (5)$$

[illegible]

DATE: 11/11/2000 11:00 AM. 11/11/2000 11:00 AM

1. The first of these is the fact that the Commission has not yet received any information from the Government of the Republic of China regarding the situation in the region of the Yangtze River.

SECRET

... 2000 ...

... 1941. 1942. 1943. 1944. 1945. 1946. 1947. 1948. 1949. 1950. 1951. 1952. 1953. 1954. 1955. 1956. 1957. 1958. 1959. 1960. 1961. 1962. 1963. 1964. 1965. 1966. 1967. 1968. 1969. 1970. 1971. 1972. 1973. 1974. 1975. 1976. 1977. 1978. 1979. 1980. 1981. 1982. 1983. 1984. 1985. 1986. 1987. 1988. 1989. 1990. 1991. 1992. 1993. 1994. 1995. 1996. 1997. 1998. 1999. 2000. 2001. 2002. 2003. 2004. 2005. 2006. 2007. 2008. 2009. 2010. 2011. 2012. 2013. 2014. 2015. 2016. 2017. 2018. 2019. 2020. 2021. 2022. 2023. 2024. 2025. 2026. 2027. 2028. 2029. 2030. 2031. 2032. 2033. 2034. 2035. 2036. 2037. 2038. 2039. 2040. 2041. 2042. 2043. 2044. 2045. 2046. 2047. 2048. 2049. 2050. 2051. 2052. 2053. 2054. 2055. 2056. 2057. 2058. 2059. 2060. 2061. 2062. 2063. 2064. 2065. 2066. 2067. 2068. 2069. 2070. 2071. 2072. 2073. 2074. 2075. 2076. 2077. 2078. 2079. 2080. 2081. 2082. 2083. 2084. 2085. 2086. 2087. 2088. 2089. 2090. 2091. 2092. 2093. 2094. 2095. 2096. 2097. 2098. 2099. 2100. 2101. 2102. 2103. 2104. 2105. 2106. 2107. 2108. 2109. 2110. 2111. 2112. 2113. 2114. 2115. 2116. 2117. 2118. 2119. 2120. 2121. 2122. 2123. 2124. 2125. 2126. 2127. 2128. 2129. 2130. 2131. 2132. 2133. 2134. 2135. 2136. 2137. 2138. 2139. 2140. 2141. 2142. 2143. 2144. 2145. 2146. 2147. 2148. 2149. 2150. 2151. 2152. 2153. 2154. 2155. 2156. 2157. 2158. 2159. 2160. 2161. 2162. 2163. 2164. 2165. 2166. 2167. 2168. 2169. 2170. 2171. 2172. 2173. 2174. 2175. 2176. 2177. 2178. 2179. 2180. 2181. 2182. 2183. 2184. 2185. 2186. 2187. 2188. 2189. 2190. 2191. 2192. 2193. 2194. 2195. 2196. 2197. 2198. 2199. 2200. 2201. 2202. 2203. 2204. 2205. 2206. 2207. 2208. 2209. 2210. 2211. 2212. 2213. 2214. 2215. 2216. 2217. 2218. 2219. 2220. 2221. 2222. 2223. 2224. 2225. 2226. 2227. 2228. 2229. 2230. 2231. 2232. 2233. 2234. 2235. 2236. 2237. 2238. 2239. 2240. 2241. 2242. 2243. 2244. 2245. 2246. 2247. 2248. 2249. 2250. 2251. 2252. 2253. 2254. 2255. 2256. 2257. 2258. 2259. 2260. 2261. 2262. 2263. 2264. 2265. 2266. 2267. 2268. 2269. 2270. 2271. 2272. 2273. 2274. 2275. 2276. 2277. 2278. 2279. 2280. 2281. 2282. 2283. 2284. 2285. 2286. 2287. 2288. 2289. 2290. 2291. 2292. 2293. 2294. 2295. 2296. 2297. 2298. 2299. 2300. 2301. 2302. 2303. 2304. 2305. 2306. 2307. 2308. 2309. 2310. 2311. 2312. 2313. 2314. 2315. 2316. 2317. 2318. 2319. 2320. 2321. 2322. 2323. 2324. 2325. 2326. 2327. 2328. 2329. 2330. 2331. 2332. 2333. 2334. 2335. 2336. 2337. 2338. 2339. 2340. 2341. 2342. 2343. 2344. 2345. 2346. 2347. 2348. 2349. 2350. 2351. 2352. 2353. 2354. 2355. 2356. 2357. 2358. 2359. 2360. 2361. 2362. 2363. 2364. 2365. 2366. 2367. 2368. 2369. 2370. 2371. 2372. 2373. 2374. 2375. 2376. 2377. 2378. 2379. 2380. 2381. 2382. 2383. 2384. 2385. 2386. 2387. 2388. 2389. 2390. 2391. 2392. 2393. 2394. 2395. 2396. 2397. 2398. 2399. 2400. 2401. 2402. 2403. 2404. 2405. 2406. 2407. 2408. 2409. 2410. 2411. 2412. 2413. 2414. 2415. 2416. 2417. 2418. 2419. 2420. 2421. 2422. 2423. 2424. 2425. 2426. 2427. 2428. 2429. 2430. 2431. 2432. 2433. 2434. 2435. 2436. 2437. 2438. 2439. 2440. 2441. 2442. 2443. 2444. 2445. 2446. 2447. 2448. 2449. 2450. 2451. 2452. 2453. 2454. 2455. 2456. 2457. 2458. 2459. 2460. 2461. 2462. 2463. 2464. 2465. 2466. 2467. 2468. 2469. 2470. 2471. 2472. 2473. 2474. 2475. 2476. 2477. 2478. 2479. 2480. 2481. 2482. 2483. 2484. 2485. 2486. 2487. 2488. 2489. 2490. 2491. 2492. 2493. 2494. 2495. 2496. 2497. 2498. 2499. 2500. 2501. 2502. 2503. 2504. 2505. 2506. 2507. 2508. 2509. 2510. 2511. 2512. 2513. 2514. 2515. 2516. 2517. 2518. 2519. 2520. 2521. 2522. 2523. 2524. 2525. 2526. 2527. 2528. 2529. 2530. 2531. 2532. 2533. 2534. 2535. 2536. 2537. 2538. 2539. 2540. 2541. 2542. 2543. 2544. 2545. 2546. 2547. 2548. 2549. 2550. 2551. 2552. 2553. 2554. 2555. 2556. 2557. 2558. 2559. 2560. 2561. 2562. 2563. 2564. 2565. 2566. 2567. 2568. 2569. 2570. 2571. 2572. 2573. 2574. 2575. 2576. 2577. 2578. 2579. 2580. 2581. 2582. 2583. 2584. 2585. 2586. 2587. 2588. 2589. 2590. 2591. 2592. 2593. 2594. 2595. 2596. 2597. 2598. 2599. 2600. 2601. 2602. 2603. 2604. 2605. 2606. 2607. 2608. 2609. 2610. 2611. 2612. 2613. 2614. 2615. 2616. 2617. 2618. 2619. 2620. 2621. 2622.

... 1913 ...

[illegible]

and it will be a pleasure to have you visit us at our home.

... ..

... ..

[illegible]

THE UNIVERSITY OF CHICAGO PRESS

[illegible]

... 300 ...

1. The first part of the document is a list of names and titles, including "The Hon. Mr. Justice" and "The Hon. Mr. Justice".

Then

$$(A/na) = (d/L)/f \quad (6)$$

From which

$$R_o/R_w = (d/L)^2/f \quad (7)$$

where  $(d/L)^2 = T$ , is termed the tortuosity of the system.

Rewriting equation (7)

$$R_o/R_w = T/f \quad (7a)$$

which is at variance to the relationship  $R_o/R_w = T^{1/2}/f$  developed by Wyllie and Rose<sup>(9)</sup> as a definition of formation factor because they based their development on the relation  $f = na/A$ , which is true only for the capillary tube where  $d/L = 1$ .

When the electrical and hydraulic flow paths are the same, when no electrically conductive solids are present the permeability may also be expressed as a function of the tortuosity. Rose and Bruce<sup>(10)</sup> express the hydraulic permeability of a porous matrix by the following relation:

$$K = (fm^2/k_o)(1/T) \quad (8)$$

in which  $K$  is the permeability,  
 $m$  is the mean hydraulic radius  $= f/A_1$ ,  
 $A_1$  is the surface area per unit volume of the matrix forming the pore channels,  
 $k_o$  is a constant of streamline motion derived from the Kozeny equation, and  
 $f$  is the fractional porosity.

This may be written as

$$K = (f^3t)/(A_1^2k_o) \quad (9)$$

where  $t = 1/T$

For any saturation of the wetting phase the effective porosity of this phase will be equal to the product of the porosity at complete

1941

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840. 84

*Journal of Management Studies*, 1986, 23(1), 7-10.

1. The first group of people who are interested in the study of the history of the United States are the people who are interested in the history of the United States.

77

[illegible]

1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2033, 2034, 2035, 2036, 2037, 2038, 2039, 2040, 2041, 2042, 2043, 2044, 2045, 2046, 2047, 2048, 2049, 2050, 2051, 2052, 2053, 2054, 2055, 2056, 2057, 2058, 2059, 2060, 2061, 2062, 2063, 2064, 2065, 2066, 2067, 2068, 2069, 2070, 2071, 2072, 2073, 2074, 2075, 2076, 2077, 2078, 2079, 2080, 2081, 2082, 2083, 2084, 2085, 2086, 2087, 2088, 2089, 2090, 2091, 2092, 2093, 2094, 2095, 2096, 2097, 2098, 2099, 2100, 2101, 2102, 2103, 2104, 2105, 2106, 2107, 2108, 2109, 2110, 2111, 2112, 2113, 2114, 2115, 2116, 2117, 2118, 2119, 2120, 2121, 2122, 2123, 2124, 2125, 2126, 2127, 2128, 2129, 2130, 2131, 2132, 2133, 2134, 2135, 2136, 2137, 2138, 2139, 2140, 2141, 2142, 2143, 2144, 2145, 2146, 2147, 2148, 2149, 2150, 2151, 2152, 2153, 2154, 2155, 2156, 2157, 2158, 2159, 2160, 2161, 2162, 2163, 2164, 2165, 2166, 2167, 2168, 2169, 2170, 2171, 2172, 2173, 2174, 2175, 2176, 2177, 2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214, 2215, 2216, 2217, 2218, 2219, 2220, 2221, 2222, 2223, 2224, 2225, 2226, 2227, 2228, 2229, 2230, 2231, 2232, 2233, 2234, 2235, 2236, 2237, 2238, 2239, 2240, 2241, 2242, 2243, 2244, 2245, 2246, 2247, 2248, 2249, 2250, 2251, 2252, 2253, 2254, 2255, 2256, 2257, 2258, 2259, 2260, 2261, 2262, 2263, 2264, 2265, 2266, 2267, 2268, 2269, 2270, 2271, 2272, 2273, 2274, 2275, 2276, 2277, 2278, 2279, 2280, 2281, 2282, 2283, 2284, 2285, 2286, 2287, 2288, 2289, 2290, 2291, 2292, 2293, 2294, 2295, 2296, 2297, 2298, 2299, 2300, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2310, 2311, 2312, 2313, 2314, 2315, 2316, 2317, 2318, 2319, 2320, 2321, 2322, 2323, 2324, 2325, 2326, 2327, 2328, 2329, 2330, 2331, 2332, 2333, 2334, 2335, 2336, 2337, 2338, 2339, 2340, 2341, 2342, 2343, 2344, 2345, 2346, 2347, 2348, 2349, 2350, 2351, 2352, 2353, 2354, 2355, 2356, 2357, 2358, 2359, 2360, 2361, 2362, 2363, 2364, 2365, 2366, 2367, 2368, 2369, 2370, 2371, 2372, 2373, 2374, 2375, 2376, 2377, 2378, 2379, 2380, 2381, 2382, 2383, 2384, 2385, 2386, 2387, 2388, 2389, 2390, 2391, 2392, 2393, 2394, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405, 2406, 2407, 2408, 2409, 2410, 2411, 2412, 2413, 2414, 2415, 2416, 2417, 2418, 2419, 2420, 2421, 2422, 2423, 2424, 2425, 2426, 2427, 2428, 2429, 2430, 2431, 2432, 2433, 2434, 2435, 2436, 2437, 2438, 2439, 2440, 2441, 2442, 2443, 2444, 2445, 2446, 2447, 2448, 2449, 2450, 2451, 2452, 2453, 2454, 2455, 2456, 2457, 2458, 2459, 2460, 2461, 2462, 2463, 2464, 2465, 2466, 2467, 2468, 2469, 2470, 2471, 2472, 2473, 2474, 2475, 2476, 2477, 2478, 2479, 2480, 2481, 2482, 2483, 2484, 2485, 2486, 2487, 2488, 2489, 2490, 2491, 2492, 2493, 2494, 2495, 2496, 2497, 2498, 2499, 2500, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2518, 2519, 2520, 2521, 2522, 2523, 2524, 2525, 2526, 2527, 2528, 2529, 2530, 2531, 2532, 2533, 2534, 2535, 2536, 2537, 2538, 2539, 2540, 2541, 2542, 2543, 2544, 2545, 2546, 2547, 2548, 2549, 2550, 2551, 2552, 2553, 2554, 2555, 2556, 2557, 2558, 2559, 2560, 2561, 2562, 2563, 2564, 2565, 2566, 2567, 2568, 2569, 2570, 2571, 2572, 2573, 2574, 2575, 2576, 2577, 2578, 2579, 2580, 2581, 2582, 2583, 2584, 2585, 2586, 2587, 2588, 2589, 2590, 2591, 2592, 2593, 2594, 2595, 2596, 2597, 2598, 2599, 2600, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2616, 2617, 2618, 2619, 2620, 2621, 2622, 2623, 2624, 2625, 2626, 2627, 2628, 2629, 2630, 2631, 2632, 2633, 2634, 2635, 2636, 2637, 2638, 2639, 2640, 2641, 2642, 2643, 2644, 2645, 2646, 2647, 2648, 2649, 2650, 2651, 2652, 2653, 2654, 2655, 2656, 2657, 2658, 2659, 2660, 2661, 2662, 2663, 2664, 2665, 2666, 2667, 2668, 2669, 2670, 2671, 2672, 2673, 2674, 2675, 2676, 2677, 2678, 26

1980年12月26日 星期日 晴 12月26日 星期日 晴

• 1 2 3 4 5 6 7 8 9 10 11 12

1. *Staphylococcus aureus*

2022



saturation times the fractional saturation.

$$f_o = Sf \quad (10)$$

Then for any saturation in which  $S$  is less than 1.0

$$K_1 = (f_o^3 t) / (A_1^2 k_o) \quad (11)$$

From equation (7a)

$$t = (R_w / R_1) / f_o \quad (7b)$$

Then

$$\begin{aligned} K_1 &= (f_o^2 / A_1^2 k_o) (R_w / R_1) \\ &= (f^2 S^2 / A_1^2 k_o) (R_w / R_1) \end{aligned} \quad (12)$$

Writing permeability at  $S = 1.0$  as the homogeneous fluid permeability  $K$ , and the permeability at  $S = 1.0$  as  $K_w$ , and similarly the resistivity at  $S = 1.0$  as  $R_o$ , and at  $S = 1.0$  as  $R$ , the ratio  $K_w/K$  becomes:

$$\frac{K_w}{K} = \frac{(f^2 S^2 / A_1^2 k_o) (R_w / R)}{(f^2 / A_1^2 k_o) (R_w / R_o)}$$

or

$$K_w/K = S^2 (R_o/R) \quad (13)$$

In which  $K_w/K$  is the relative permeability to the wetting phase as currently defined in the literature, and  $R_o/R$  is a new concept termed the relative resistivity.

#### ANALYSIS OF DATA

From equation (13) it may be seen that the relative permeability and relative resistivity are both functions of the wetting phase saturation.

PROPOSITION 1. Let  $f$  be a function on  $\mathbb{R}^n$  such that

$$(I) \quad f(x) = 0 \quad \text{for } |x| \geq 1$$

and let  $\mu$  be a measure on  $\mathbb{R}^n$  such that

$$(II) \quad \int_{\mathbb{R}^n} f(x) d\mu(x) = 0$$

then

$$(III) \quad \int_{\mathbb{R}^n} f(x) d\mu(x) = 0$$

and

$$(IV) \quad \int_{\mathbb{R}^n} f(x) d\mu(x) = 0$$

$$(V) \quad \int_{\mathbb{R}^n} f(x) d\mu(x) = 0$$

PROOF. Let  $\mu$  be a measure on  $\mathbb{R}^n$  such that

(I)  $\mu$  is a finite measure on  $\mathbb{R}^n$  and

(II)  $\int_{\mathbb{R}^n} f(x) d\mu(x) = 0$  and

then

$$\int_{\mathbb{R}^n} f(x) d\mu(x) = 0$$

and

$$\int_{\mathbb{R}^n} f(x) d\mu(x) = 0$$

PROOF. Let  $\mu$  be a measure on  $\mathbb{R}^n$  such that

(I)  $\mu$  is a finite measure on  $\mathbb{R}^n$  and

(II)  $\int_{\mathbb{R}^n} f(x) d\mu(x) = 0$  and

then

$$\int_{\mathbb{R}^n} f(x) d\mu(x) = 0$$

PROOF. Let  $\mu$  be a measure on  $\mathbb{R}^n$  such that

Referring to the data of Wyckoff and Botset<sup>(11)</sup>, values of relative permeability to the wetting phase for a clean unconsolidated sand result in a linear relation with saturation on logarithmic coordinates. Figure (5) of the paper by Dunlap and his co-workers<sup>(7)</sup> is a plot of the resistance of a clean unconsolidated sand against saturation. From these data the quantity  $(R_0/R)S^2$  may be calculated. This function is then plotted on logarithmic coordinates against saturation and a straight line may be drawn through Dunlap's experimental data plotted in this manner. For the resistivity function in the region where  $S < 0.3$  the fit is excellent. Above this region the experimental points are spread, possibly because of non-uniform saturation. Because no information is available on the gradient of such possible saturation variation, the line represents an "eyeball" average of the data.

These two sets of data are shown on Figure (1). The vertical axes represent the right and left sides of equation (13), and the horizontal axis represents the fractional wetting phase saturation.

Despite the fact that over ten years separate the times of obtaining these two sets of data, and despite the fact that the properties of different sands were being investigated, close agreement is obtained between the two lines. Thus it can be said that the function of saturation involved is the same for both parameters.

Thus the equations of these two lines are

$$S^{u-2} = R_0/R \quad (14a)$$

$$S^u = K_w/K \quad (14b)$$

where  $u$  is the slope of the lines.

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

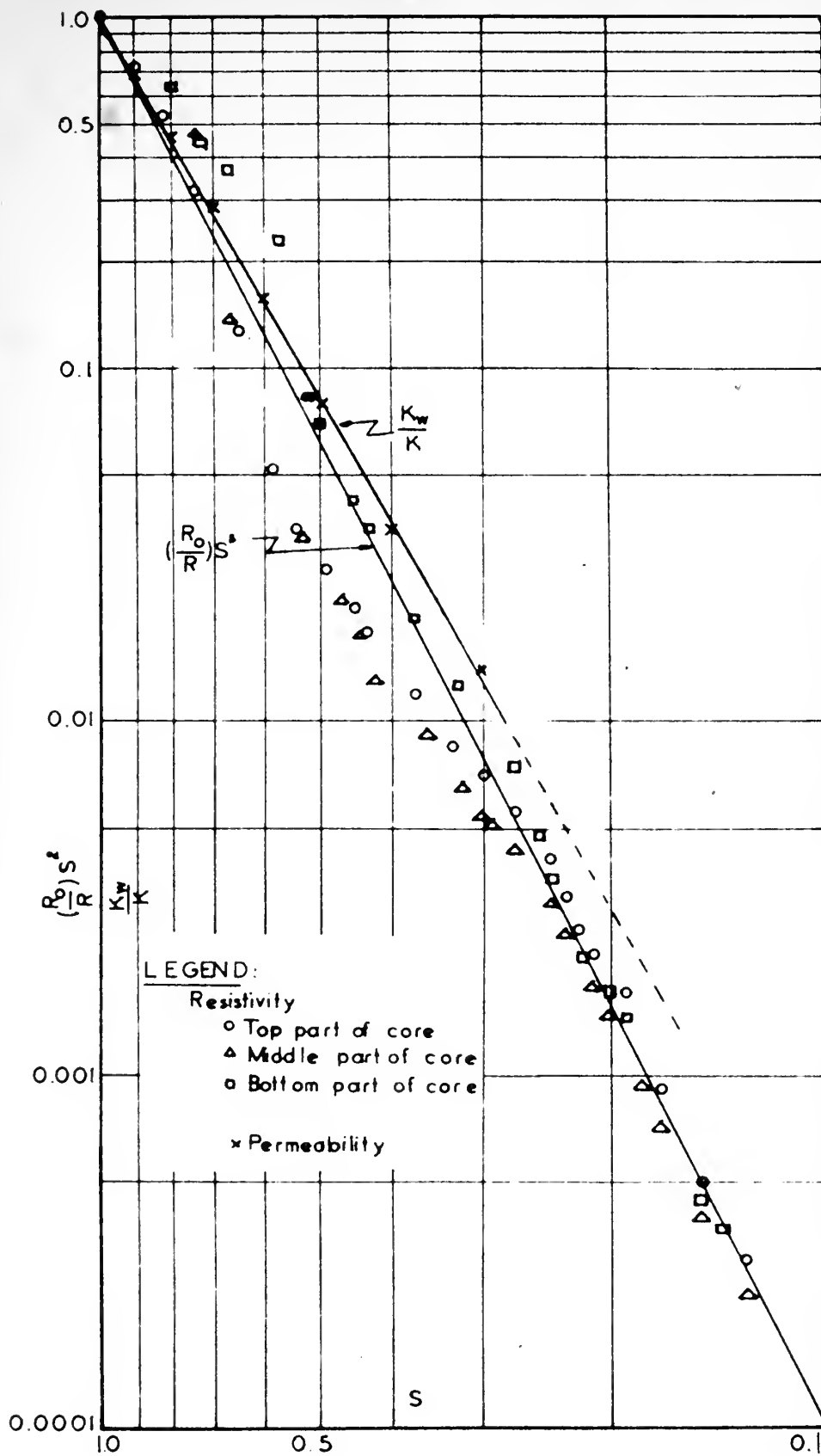
...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...

...to the ... of the ...



UNCONSOLIDATED  
SANDS

RELATIONSHIP  
BETWEEN RESISTIVITY,  
PERMEABILITY, AND  
SATURATION

Relative Resistivity Data  
After Dunlap (1)

Relative Permeability  
Data after Wyckoff &  
Botset (11)

FIGURE 1.



Then

$$K_w/K = (R_0/R)^{u/(u-2)} \quad (15)$$

The slope of the lines in Figure (1) is equal to 4. Equation (15) then becomes

$$K_w/K = (R_0/R)^2 \quad (16)$$

or for clean, unconsolidated sands the relative permeability to the wetting phase is equal to the square of the relative resistivity.

Going back to equation (14a), for  $u = 4$

$$R_0/R = S^2 \quad (17)$$

Thus for clean, unconsolidated sands, the relation postulated by Archie<sup>(2)</sup>, using an exponent of 2, is quite valid.

For consolidated sands the data available in the literature are not definitive. Using the data of Morse and his co-workers<sup>(12)</sup>, for consolidated sands, the right and left sides of equation (13) are again plotted against saturation on logarithmic coordinates, Figure (2). The lines thus obtained are not as good as those of Figure (1), but yield a slope of approximately 6.0.

Then for consolidated sands approximate relations may be written

$$K_w/K = (R_0/R)^{1.5} \quad (18)$$

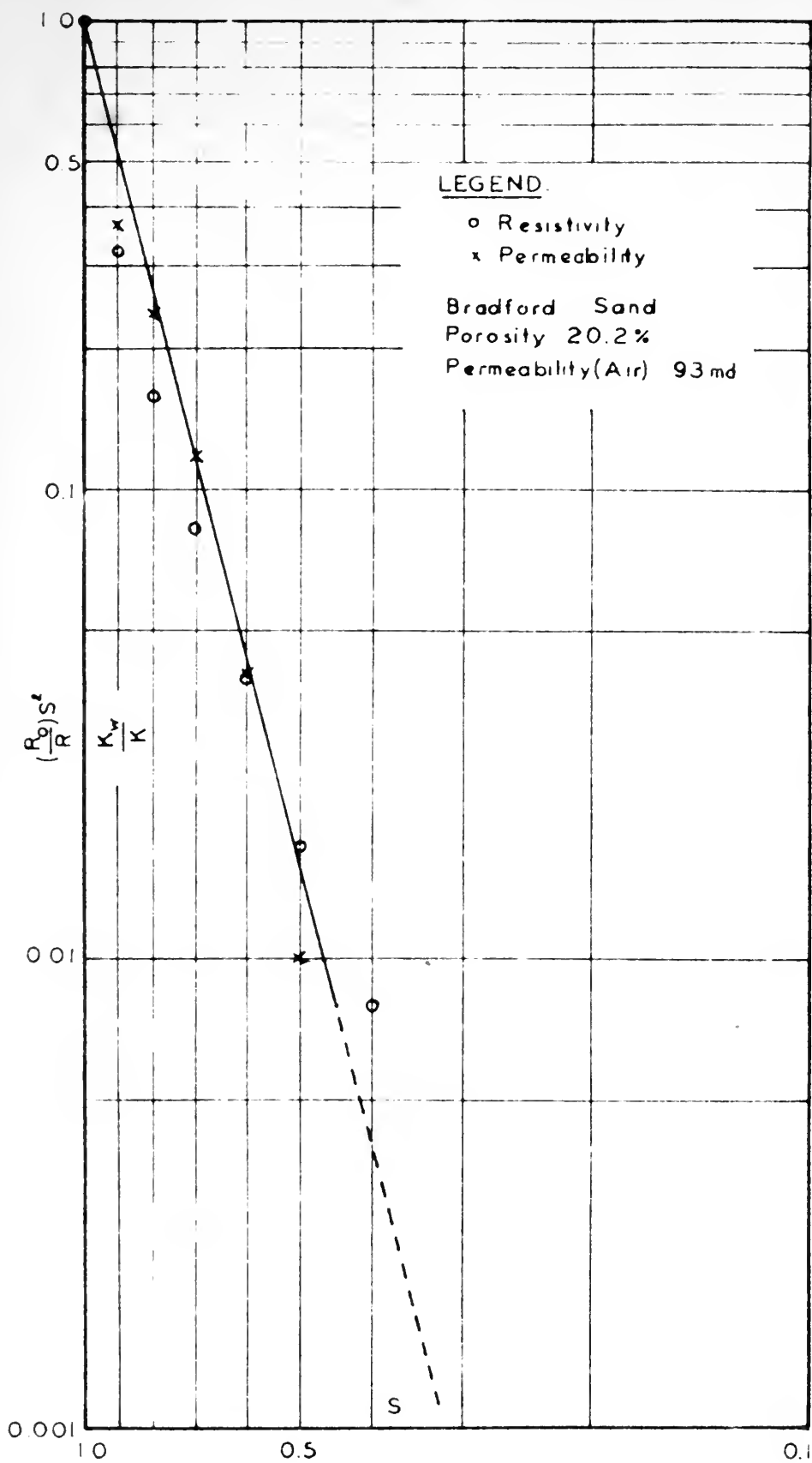
$$S^4 = R_0/R \quad (19)$$

Because of the dearth of data for consolidated sands equations (18) and (19) are presented only as qualitative relations.

Considering the case of the capillary tube, it is known that the resistivity varies linearly with the saturation. From this the function  $(R_0/R)S^2$  may be calculated and plotted against saturation. Figure (3) shows the slope of this line to be three.







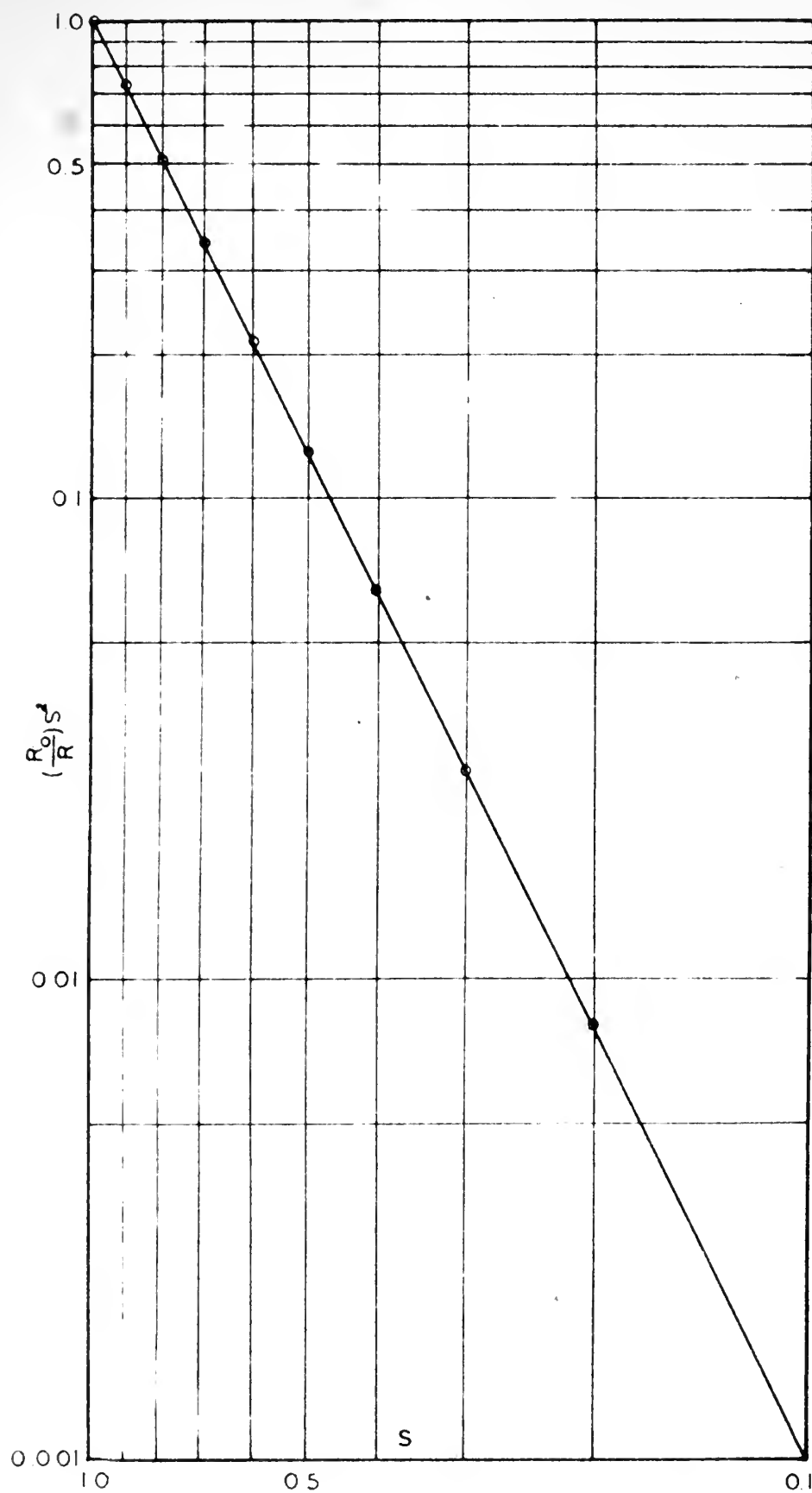
CONSOLIDATED  
SANDS

RELATIONSHIP  
BETWEEN RESISTIVITY,  
PERMEABILITY, AND  
SATURATION

Data After Morse (12)

FIGURE 2.





CAPILLARY  
TUBE

RELATIONSHIP  
BETWEEN RESISTIVITY  
AND SATURATION

FIGURE 3.



Thus for a capillary tube

$$S^{u-2} = R_0/R$$

or

$$S = R_0/R \quad (20)$$

which relation is indeed valid.

It must be remembered, however, that these relationships are applicable only when the hydraulic and electric flow paths are the same, or when there are no conducting solids to conduct the electricity to the exclusion of fluid flow.

Additional data are available in the literature in the work of previous investigators<sup>(14)(15)</sup>. These data along with those previously used are shown in tabular form in Appendix II and the source of each is indicated. In all cases, in order to obtain relative permeability and relative resistivity values at the same saturations, these values were taken from the curves drawn by these previous investigators rather than the experimental points themselves. These data are grouped for unconsolidated sands, consolidated sands, and synthetic consolidated cores.

Using the arithmetic average of the four sets of data given in Tables I through IV (Appendix II), three curves were plotted on rectangular coordinates, (Figure 4.). The first curve is a plot of relative resistivity versus saturation, the second is a plot of relative permeability to the wetting phase versus saturation, and the third is a plot of relative resistivity squared versus saturation. The spread of the relative resistivity data used to obtain curve 1 of Figure (4), is shown by Figure (8), Appendix II. The close agreement of curves 2 and 3 supports the

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

1954

1954

RECEIVED

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

1954

1954

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

1954

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

1954

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

1954

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

1954

THE UNIVERSITY OF CHICAGO

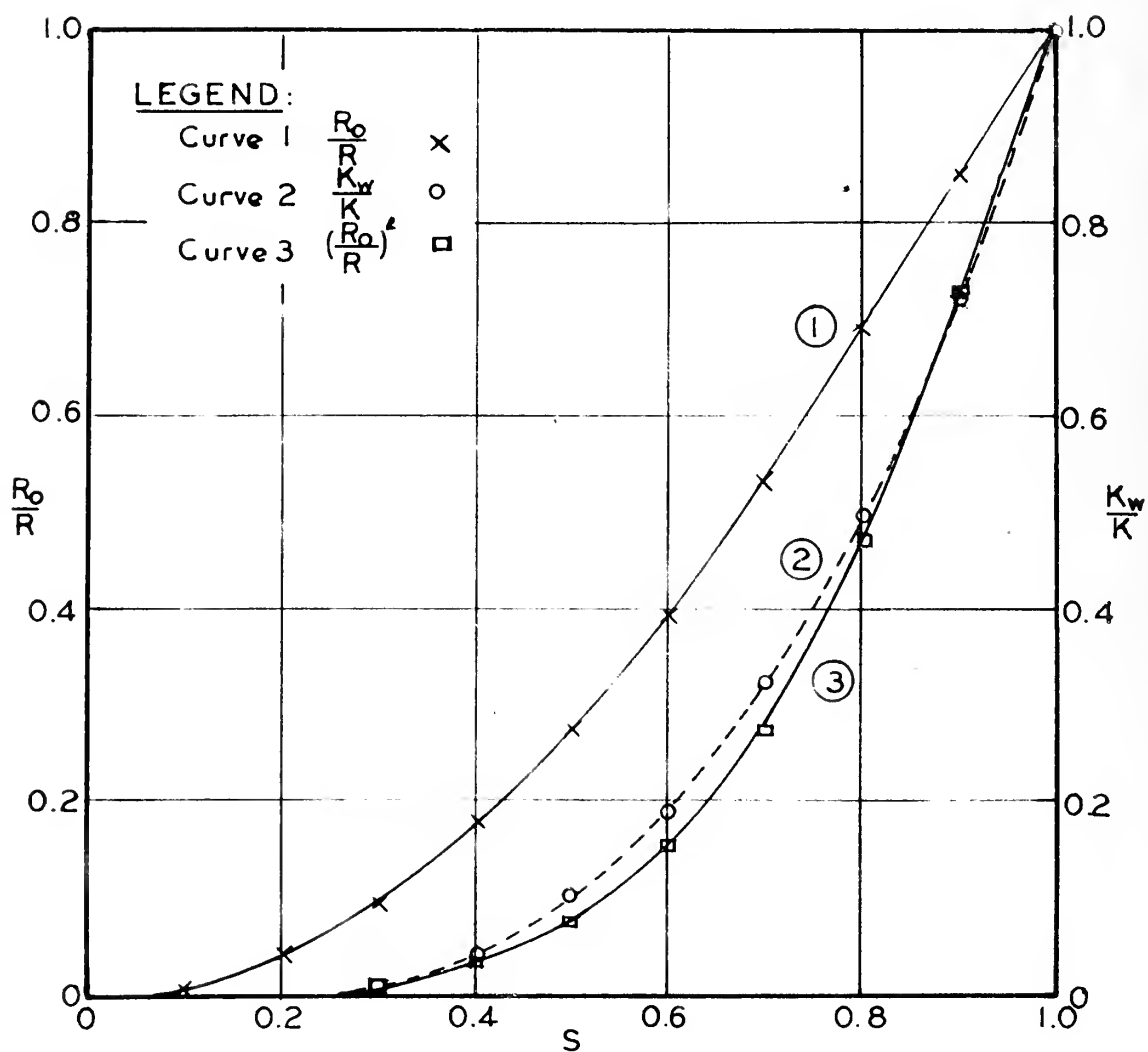
PHYSICS DEPARTMENT

1954

THE UNIVERSITY OF CHICAGO

PHYSICS DEPARTMENT

AVERAGE VALUES OF RELATIVE RESISTIVITY  
AND RELATIVE PERMEABILITY FOR  
UNCONSOLIDATED SANDS  
 (TABLE V)



NOTE: Curves 2 and 3 show relationship  $\frac{K_w}{K} = \left(\frac{R_0}{R}\right)^2$ ,  
 Equation (16)

FIGURE 4.





relationship given by equation (16).

Referring to the data given by Morse<sup>(12)</sup> for a Bradford sand, (Table VI, Appendix II), curves similar to those drawn for the unconsolidated sand are shown for this one set of data on a consolidated sand, Figure (5). In addition a fourth curve is drawn to represent the right hand side of equation (13). The fair agreement between curves 2 and 4 tends to support the relation given by equation (13) for this set of data.

Finally using the data for a synthetic core given by Morse (12) the three curves shown in Figure (4) are plotted for a synthetic core, (Table VII, Appendix). Figure (6) shows these relationships but the data available for this case were so scant that no definite conclusions may be drawn therefrom, except that this set of data gives excellent support to equation (16).

If all the data and the fundamental ideas developed above are considered together in a more general sense an additional possible aspect of the relationship becomes apparent. It may be noted that for the cases of the unconsolidated sands and the synthetic core the data available are in agreement with the relationships

$$\begin{aligned} K_w/K &= (R_o/R)^2 & \text{and} \\ R_o/R &= g^2 \end{aligned}$$

The main point of physical similarity between the unconsolidated sands and the synthetic core is that both are, to all practical purposes, isotropic. There are no bedding planes and no stratification. With this in mind, note that for the case of the capillary tube the relation between relative

relationship given by equation (10),

reference to the data of Figure 10 is made.

(Table VI, Appendix II), which are shown in Figure 10.

and are shown in Figure 10. The data are shown in Figure 10.

In addition, Figure 10 shows the data for the case of a

constant  $\alpha$ , which is shown in Figure 10.

the data for the case of a constant  $\alpha$  are shown in Figure 10.

Figure 10 shows the data for the case of a constant  $\alpha$ .

the data for the case of a constant  $\alpha$  are shown in Figure 10.

(Table VII, Appendix II), which are shown in Figure 10.

data for the case of a constant  $\alpha$  are shown in Figure 10.

may be obtained from the data for the case of a constant  $\alpha$ .

appears to be a constant (10).

Figure 10 shows the data for the case of a constant  $\alpha$ .

conclusion is that the data for the case of a constant  $\alpha$  are shown in Figure 10.

Figure 10 shows the data for the case of a constant  $\alpha$ .

Figure 10 shows the data for the case of a constant  $\alpha$ .

are shown in Figure 10.

Figure 10 shows the data for the case of a constant  $\alpha$ .

Figure 10 shows the data for the case of a constant  $\alpha$ .

Figure 10 shows the data for the case of a constant  $\alpha$ .

Figure 10 shows the data for the case of a constant  $\alpha$ .

Figure 10 shows the data for the case of a constant  $\alpha$ .

Figure 10 shows the data for the case of a constant  $\alpha$ .

RELATIONSHIP BETWEEN RELATIVE RESISTIVITY  
AND RELATIVE PERMEABILITY FOR  
A CONSOLIDATED SAND  
 Data After Morse (12)

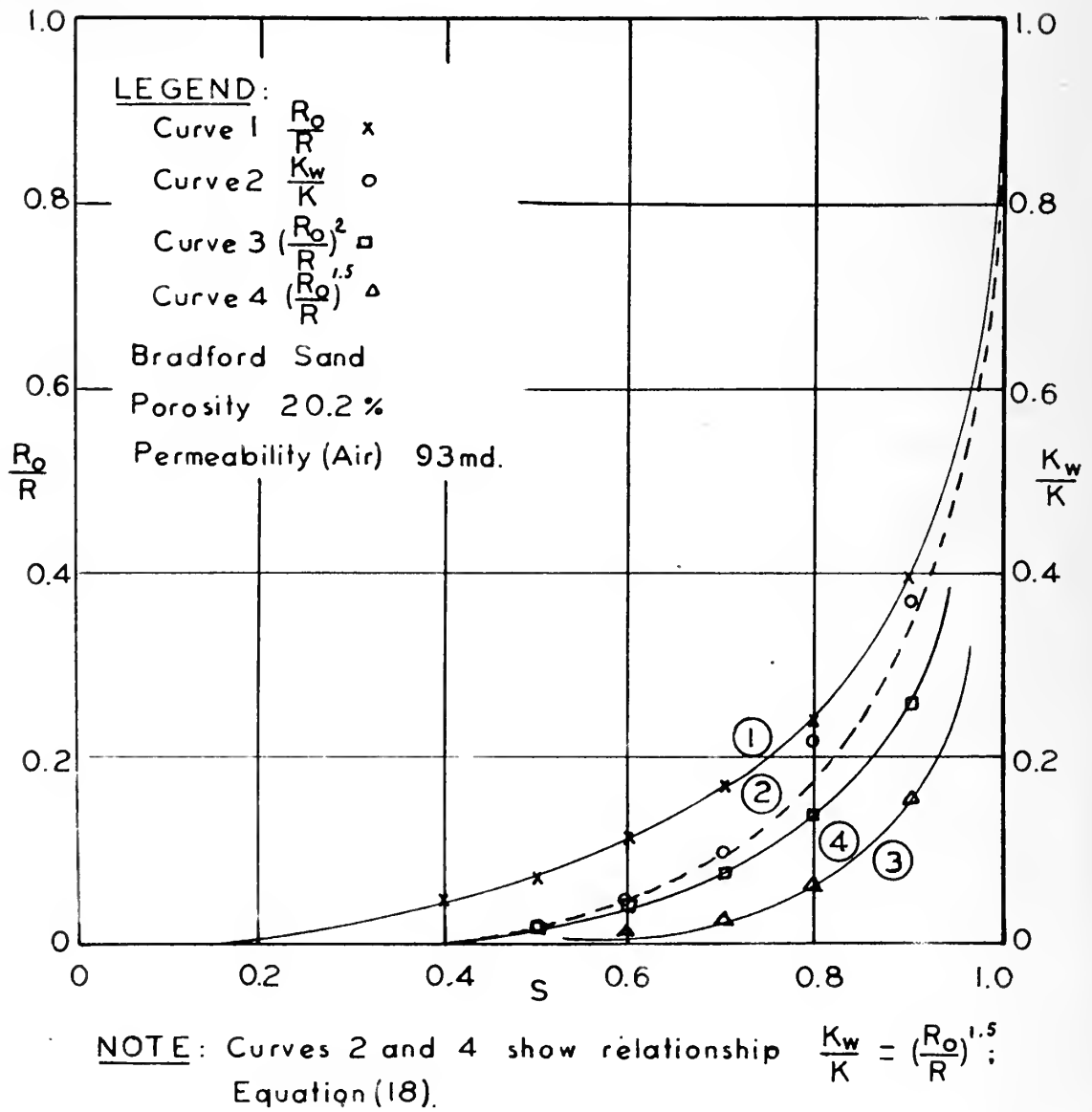
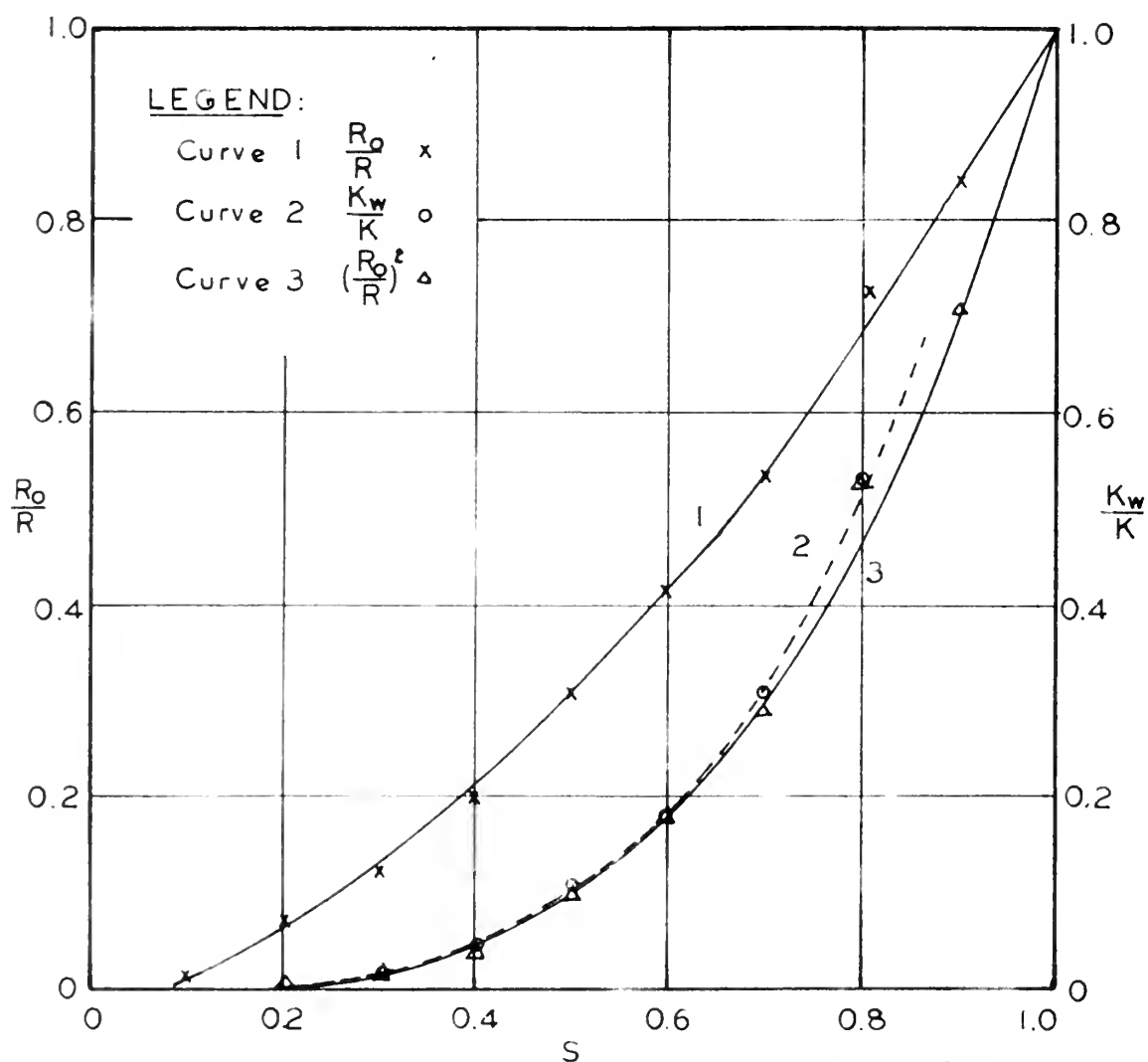


FIGURE 5.



RELATIONSHIP BETWEEN RELATIVE RESISTIVITY  
AND RELATIVE PERMEABILITY FOR A  
CONSOLIDATED SYNTHETIC CORE

Data After Morse (12).



NOTE: Curves 2 and 3 show relationship  $\frac{K_w}{K} = (\frac{R_0}{R})^2$ ;  
Equation (16).

FIGURE 6.



resistivity and saturation is

$$R_0/R = S$$

Consider, in this light, the case of a consolidated sand with more or less stratification. If the planes of stratification are such that flow paths are no longer random, then preferential flow channels will be established either in the general direction of flow or across the general direction of flow. If along the direction of flow the conditions will tend toward those of the capillary tube, and the relation between relative resistivity and saturation will become

$$R_0/R = S^n \quad \text{where } n < 2$$

If stratification is more pronounced across the direction of electrical flow the conditions will be on the other side of isotropic conditions, and

$$R_0/R = S^n \quad \text{where } n > 2$$

#### PROPOSED FUTURE RESEARCH

Since the data presented are somewhat varied and were not gathered with this problem specifically in mind they are not ideally suited for the confirmation of the relationships postulated. It would therefore be desirable to obtain additional data under circumstances controlled to point up the effects considered.

Although it is felt that the fluid distribution within a core, as well as the actual saturation, will effect the resistivity the initial step in the analysis should be to establish this fact experimentally .

Such experimental verification on a macroscopic level could be obtained by placing a partially saturated core in a centrifuge and

Respectfully,  
[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

[Signature]

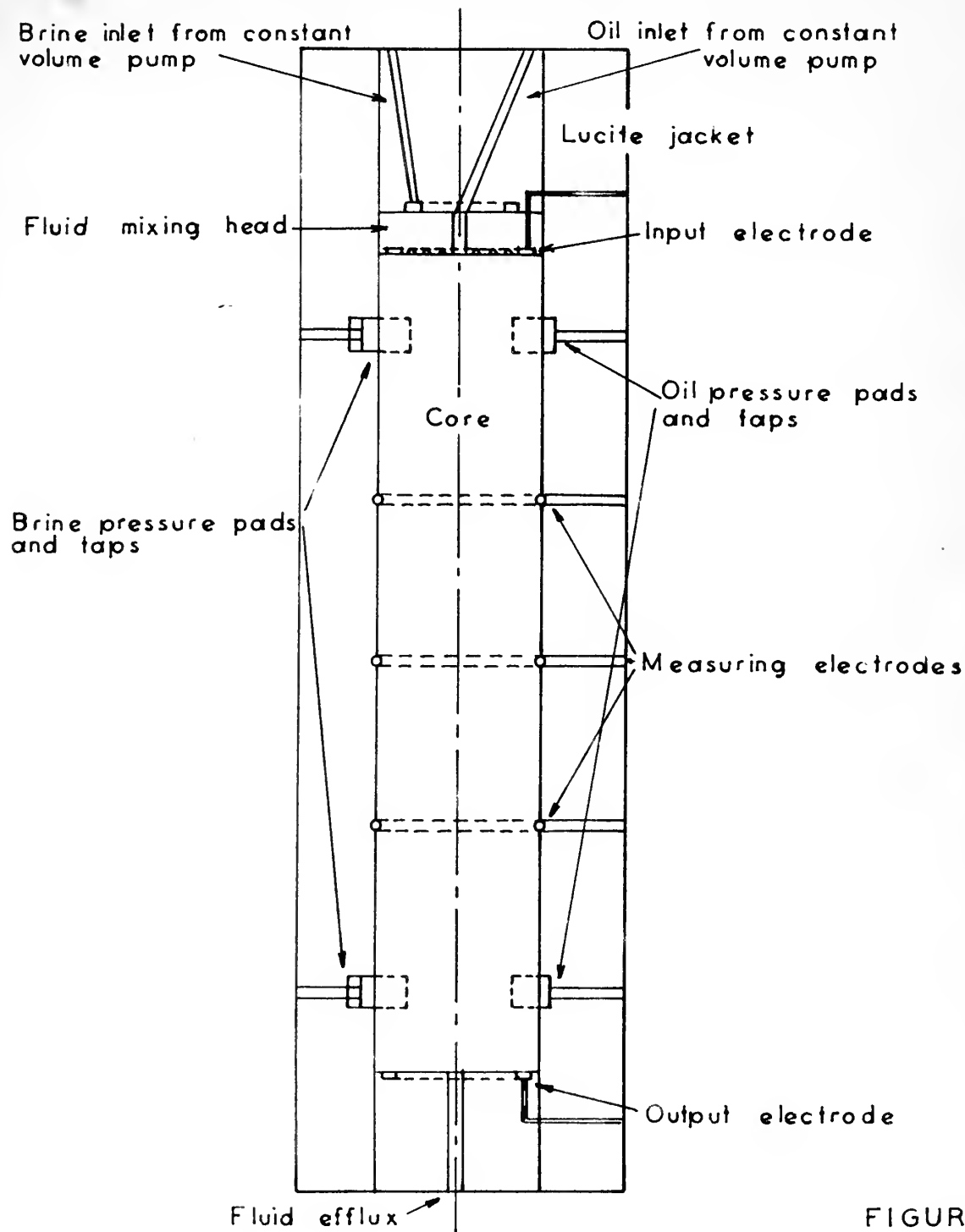
[Signature]

[Signature]

[Signature]



# EXPERIMENTAL SETUP FOR MEASURING RESISTIVITY AND PERMEABILITY Vertical Cross Section



Scale: 1" = 1"

FIGURE 7.



rotating the centrifuge at velocities sufficiently high to obtain definite amounts of fluid migration. As the orientations of the core were changed fluid migrations would take place to various parts of the core and fluid distributions would be changed. The rotor of the centrifuge must be fitted with slip rings to measure the resistivity of the core while the centrifuge is rotating. A control plug of known, and constant resistivity must be placed in the centrifuge to keep a check on circuit variations. Such a study would show the effect of changes in the macroscopic fluid distribution within the core. Microscopic variations would probably have an effect upon the resistivity, as indicated in the earlier discussion, but these variations would be masked by the larger macroscopic effect.

Having established such an effect the problem of a relationship is primarily that of the relationship between hydraulic and electric flow. Thus a system in which both hydraulic and electric flow can occur must be used. Further, since there are only two electrical "phases", the conducting fluid and the non-conducting fluid, only a two phase hydraulic system is necessary. Such a system could be set up using a modification of the equipment described by Dunlap<sup>(7)</sup>, shown in Figure (7).

Knowing the homogeneous fluid permeability of the core, and its effective porosity, the core mounted in such a lucite core holder can be saturated with brine. At this saturation the voltage drops can be measured and the resistivity,  $R_0$ , can be calculated. The multiple electrodes provide a check on the uniformity of saturation.

The first of these is the fact that the system is not a simple one. It is a complex system, and the complexity is not only in the number of components, but also in the way they are interconnected. The second is the fact that the system is not a static one. It is a dynamic system, and the dynamics are not only in the way the components interact, but also in the way the system evolves over time. The third is the fact that the system is not a linear one. It is a non-linear system, and the non-linearity is not only in the way the components interact, but also in the way the system evolves over time.

The saturation can then be varied by flowing oil and water through the system at rates fixed by the constant volume pumps. When equilibrium is reached the fluid flux out will be equal to the amounts flowing in and a constant pressure drop will obtain. From these rates of flow the permeabilities to both phases can be calculated, although in this analysis only the permeability to the brine phase is required.

While the system is flowing under equilibrium conditions a voltage can be impressed across the end electrodes. The voltage across the measuring electrodes can be measured, and from this the resistivity,  $R_t$ , can be calculated. To establish whether or not the resistivity will be effected by streaming potential phenomena, hydraulic flow can be stopped, the voltage drops measured and the resistivity under static conditions calculated. It is considered that for brine concentrations greater than 0.1M this effect will be small.

This then will permit permeability and resistivity measurements to be made at various saturations. In order to make these data definitive of the conditions an independent determination of the brine saturation must be made. This might be accomplished by a mass balance, but, because of the relatively large quantities of fluid involved, the precision of this method will be poor.

A more satisfactory approach to the problem lies in saturation evaluation by X-ray analysis. If the equipment described above were mounted in X-ray equipment as described by Laird and Rutman<sup>(15)</sup>, after each set of permeability and resistivity measurements, the saturation and its distribution could be evaluated independently.

[illegible]

With data obtained in this fashion the reliability of the relationships developed above could be checked conclusively.

### CONCLUSIONS

1. It has been shown that because of the similarity between electrical and hydraulic flow a relation may be developed between electrical conductivity or resistivity and hydraulic permeability. This relationship takes the form

$$K_w/K = (R_0/R)S^2$$

2. If the saturation is eliminated from the expression, a second relation results

$$K_w/K = (R_0/R)^u/(u-2)$$

(a) Experimental data show that for clean unconsolidated sands  $u = 4$ , and

$$K_w/K = (R_0/R)^2$$

(b) For consolidated sands the data available are not as conclusive, but a qualitative relation may be written

$$K_w/K = (R_0/R)^v \quad \text{where } v < 2$$

3. It has also been shown that the relation postulated by Archie

$$S^2 = R_0/R$$

is quite valid for clean unconsolidated sands.

### TENTATIVE ADDITIONAL CONCLUSIONS

In addition to the conclusions given above the following tentative conclusions are also presented.

and the ... ..

... ..

...

... ..  
... ..  
... ..  
... ..

... ..  
... ..  
... ..

... ..  
... ..  
... ..  
... ..  
... ..  
... ..  
... ..

... ..  
... ..  
... ..  
... ..



1. For isotropic media the relative permeability to the wetting phase is equal to the square of the relative resistivity. Further, for these media, the relationship developed by Archie is valid and the exponent of the saturation is equal to 2.

2. For anisotropic media, in which the bedding lies in the direction of electrical flow, Archie's relationship is valid, but the exponent of the saturation is less than 2.

3. For anisotropic media in which the bedding is across the direction of electrical flow, Archie's relationship is valid, but the exponent of the saturation is greater than 2.

By a study of the resistivities of consolidated sands in carefully oriented positions these conclusions could be verified, and, if true, a quantitative relationship established. A study of available field data might also be used to investigate these relationships.

[illegible]

#### REFERENCES

- (1) Schlumberger Well Surveying Corp., Resistivity Departure Curves, September, 1947, 1949.
- (2) Archie, G. E., "The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics", A.I.M.E. Pet. Dev. & Tech., 1942.
- (3) Jackosky, J. J. and Hopper, R. H., "The Effects of Moisture on the Direct Current Resistivities of Oil Sands and Rocks", Geophysics, 2, 1937.
- (4) Tixier, H. P., "Evaluation of Permeability from Electric Log Resistivity Gradients", Oil & Gas Journal, 48, 16, June 16, 1949.
- (5) Archie, G. E., "Electrical resistivity as an Aid in Core Analysis Interpretation", Bull. AAPG, 31, 1947.
- (6) Martin, M., Murray, G. H., and Gillingham, V., "Determination of the Potential Productivity of Oil-bearing Formations by Resistivity Measurements", Geophysics, 3, 1938.
- (7) Durlap, E. A., Eldert, R. A., Bailey, J. A., and Butler, A., "The Relation Between Electrical Resistivity and prime saturation in Reservoir Rocks", J. Pet. Tech., October, 1949.
- (8) Henderson, H. J., and Yuster, A. A., "Studies in Relative Permeability", World Oil, 127, 1943.
- (9) Kyllie, E. K. J., and Rose, A. D., "Some Theoretical Considerations Related to the Quantitative Evaluation of the Physical Characteristics of Reservoir Rocks from Electrical Log Data", September, 1949.

Appendix

(1) Polioepitaxial Well Drilling Log, West, 1967

September, 1967, 1968

(2) Stratigraphic Column, West, 1967

Some of the data are from the West, 1967

(3) Geological Map, West, 1967

Geological map of the West, 1967

(4) Stratigraphic Column, West, 1967

Stratigraphic column of the West, 1967

(5) Geological Map, West, 1967

Geological map of the West, 1967

(6) Stratigraphic Column, West, 1967

Stratigraphic column of the West, 1967

Geological map of the West, 1967

(7) Geological Map, West, 1967

Geological map of the West, 1967

Geological map of the West, 1967

(8) Stratigraphic Column, West, 1967

Stratigraphic column of the West, 1967

(9) Geological Map, West, 1967

Geological map of the West, 1967

Geological map of the West, 1967

- (10) Rose, W. D. and Bruce, W. A., "Evaluation of Capillary Character in Petroleum Reservoir Rock", J. Pet. Tech. May, 1949.
- (11) Wyckoff, R. D. and Botset, H. G., "The Flow of Gas-Liquid Mixtures Through Unconsolidated Sands", Physica, 7, 1936.
- (12) Morse, R. A., Terwilliger, P. L., and Yuster, S. T., "Relative Permeability Measurements on Small Core Samples", Oil & Gas Journal, 46, 1947.
- (13) Botset, H. G., "Flow of Gas-Liquid Mixtures Through Consolidated Sand", A.I.M.E. Pet. Dev. & Tech., 1940.
- (14) Leverett, M. G., "The Flow of Oil-Water Mixtures Through Unconsolidated Sands", A.I.M.E. Pet. Dev. & Tech., 1939.
- (15) Kogan, I. and Khosiatzvo, A. P., "Utilization of Electrical Logging Data for the Determination of Oil Reserves", Petroleum Research Institute at Azerbaijan, Baku, 1935.
- (16) Laird, A. and Putnam, J. A., "Fluid Saturation in Porous Media by X-Ray Technique", Presented October 22, 1949, AIME meeting at Los Angeles, Calif. (In press).

1. the number of people who are in the area of the city is increasing at a rapid rate and is expected to continue to increase at a rapid rate for the next few years (11)

1941 7.10.1941 1941 7.10.1941 1941 7.10.1941 1941 7.10.1941 1941 7.10.1941 1941 7.10.1941

[illegible]

1. The first group of people who are interested in the study of the history of the United States are the people who are interested in the history of the United States.

... (faint text) ...

1. The first part of the document is a list of names and titles, including "The Hon. Mr. Justice" and "The Hon. Mr. Justice".

1. *Introduction*

[illegible]

1. The first part of the document is a list of names and titles, including "The Hon. Mr. Justice" and "The Hon. Mr. Justice".

[illegible]

... ..

7. 1964. 1965. 1966. 1967. 1968. 1969. 1970. 1971. 1972. 1973. 1974. 1975. 1976. 1977. 1978. 1979. 1980. 1981. 1982. 1983. 1984. 1985. 1986. 1987. 1988. 1989. 1990. 1991. 1992. 1993. 1994. 1995. 1996. 1997. 1998. 1999. 2000. 2001. 2002. 2003. 2004. 2005. 2006. 2007. 2008. 2009. 2010. 2011. 2012. 2013. 2014. 2015. 2016. 2017. 2018. 2019. 2020. 2021. 2022. 2023. 2024. 2025. 2026. 2027. 2028. 2029. 2030. 2031. 2032. 2033. 2034. 2035. 2036. 2037. 2038. 2039. 2040. 2041. 2042. 2043. 2044. 2045. 2046. 2047. 2048. 2049. 2050. 2051. 2052. 2053. 2054. 2055. 2056. 2057. 2058. 2059. 2060. 2061. 2062. 2063. 2064. 2065. 2066. 2067. 2068. 2069. 2070. 2071. 2072. 2073. 2074. 2075. 2076. 2077. 2078. 2079. 2080. 2081. 2082. 2083. 2084. 2085. 2086. 2087. 2088. 2089. 2090. 2091. 2092. 2093. 2094. 2095. 2096. 2097. 2098. 2099. 2100. 2101. 2102. 2103. 2104. 2105. 2106. 2107. 2108. 2109. 2110. 2111. 2112. 2113. 2114. 2115. 2116. 2117. 2118. 2119. 2120. 2121. 2122. 2123. 2124. 2125. 2126. 2127. 2128. 2129. 2130. 2131. 2132. 2133. 2134. 2135. 2136. 2137. 2138. 2139. 2140. 2141. 2142. 2143. 2144. 2145. 2146. 2147. 2148. 2149. 2150. 2151. 2152. 2153. 2154. 2155. 2156. 2157. 2158. 2159. 2160. 2161. 2162. 2163. 2164. 2165. 2166. 2167. 2168. 2169. 2170. 2171. 2172. 2173. 2174. 2175. 2176. 2177. 2178. 2179. 2180. 2181. 2182. 2183. 2184. 2185. 2186. 2187. 2188. 2189. 2190. 2191. 2192. 2193. 2194. 2195. 2196. 2197. 2198. 2199. 2200. 2201. 2202. 2203. 2204. 2205. 2206. 2207. 2208. 2209. 2210. 2211. 2212. 2213. 2214. 2215. 2216. 2217. 2218. 2219. 2220. 2221. 2222. 2223. 2224. 2225. 2226. 2227. 2228. 2229. 2230. 2231. 2232. 2233. 2234. 2235. 2236. 2237. 2238. 2239. 2240. 2241. 2242. 2243. 2244. 2245. 2246. 2247. 2248. 2249. 2250. 2251. 2252. 2253. 2254. 2255. 2256. 2257. 2258. 2259. 2260. 2261. 2262. 2263. 2264. 2265. 2266. 2267. 2268. 2269. 2270. 2271. 2272. 2273. 2274. 2275. 2276. 2277. 2278. 2279. 2280. 2281. 2282. 2283. 2284. 2285. 2286. 2287. 2288. 2289. 2290. 2291. 2292. 2293. 2294. 2295. 2296. 2297. 2298. 2299. 2300. 2301. 2302. 2303. 2304. 2305. 2306. 2307. 2308. 2309. 2310. 2311. 2312. 2313. 2314. 2315. 2316. 2317. 2318. 2319. 2320. 2321. 2322. 2323. 2324. 2325. 2326. 2327. 2328. 2329. 2330. 2331. 2332. 2333. 2334. 2335. 2336. 2337. 2338. 2339. 2340. 2341. 2342. 2343. 2344. 2345. 2346. 2347. 2348. 2349. 2350. 2351. 2352. 2353. 2354. 2355. 2356. 2357. 2358. 2359. 2360. 2361. 2362. 2363. 2364. 2365. 2366. 2367. 2368. 2369. 2370. 2371. 2372. 2373. 2374. 2375. 2376. 2377. 2378. 2379. 2380. 2381. 2382. 2383. 2384. 2385. 2386. 2387. 2388. 2389. 2390. 2391. 2392. 2393. 2394. 2395. 2396. 2397. 2398. 2399. 2400. 2401. 2402. 2403. 2404. 2405. 2406. 2407. 2408. 2409. 2410. 2411. 2412. 2413. 2414. 2415. 2416. 2417. 2418. 2419. 2420. 2421. 2422. 2423. 2424. 2425. 2426. 2427. 2428. 2429. 2430. 2431. 2432. 2433. 2434. 2435. 2436. 2437. 2438. 2439. 2440. 2441. 2442. 2443. 2444. 2445. 2446. 2447. 2448. 2449. 2450. 2451. 2452. 2453. 2454. 2455. 2456. 2457. 2458. 2459. 2460. 2461. 2462. 2463. 2464. 2465. 2466. 2467. 2468. 2469. 2470. 2471. 2472. 2473. 2474. 2475. 2476. 2477. 2478. 2479. 2480. 2481. 2482. 2483. 2484. 2485. 2486. 2487. 2488. 2489. 2490. 2491. 2492. 2493. 2494. 2495. 2496. 2497. 2498. 2499. 2500. 2501. 2502. 2503. 2504. 2505. 2506. 2507. 2508. 2509. 2510. 2511. 2512. 2513. 2514. 2515. 2516. 2517. 2518. 2519. 2520. 2521. 2522. 2523. 2524. 2525. 2526. 2527. 2528. 2529. 2530. 2531. 2532. 2533. 2534. 2535. 2536. 2537. 2538. 2539. 2540. 2541. 2542. 2543. 2544. 2545. 2546. 2547. 2548. 2549. 2550. 2551. 2552. 2553. 2554. 2555. 2556. 2557. 2558. 2559. 2560. 2561. 2562. 2563. 2564. 2565. 2566. 2567. 2568. 2569. 2570. 2571. 2572. 2573. 2574. 2575. 2576. 2577. 2578. 2579. 2580. 2581. 2582. 2583. 2584. 2585. 2586. 2587. 2588. 2589. 2590. 2591. 2592. 2593. 2594. 2595. 2596. 2597. 2598. 2599. 2600. 2601. 2602. 2603. 2604. 2605. 2606. 2607. 2608. 2609. 2610. 2611. 2612. 2613. 2614. 2615. 2616. 2617. 2618. 2619. 2620. 2621. 2622. 2623. 2624. 2625. 2626. 2627. 2628. 2629. 2630. 2631. 2632. 2633. 2634. 2635. 2636. 2637. 2638. 2639. 2640. 2641. 2642. 2643. 2644. 2645.

*Journal of Management Education* 30(6)p.789-804

## APPENDIX I

ESTIMATION OF RELATIVE PERMEABILITY  
IN CERTAIN IDEALIZED PORE SPACES

12/11/11

12/11/11 12:11 PM 12/11/11

12/11/11 12:11 PM 12/11/11



## Evaluation of Relative Resistivity in Certain Idealized Pore Spaces

To determine whether or not a definite relationship can be established to predict the variation in resistivity with saturation in any porous matrix, this variation was studied in certain idealized pore spaces. The pore spaces studied in detail were (1) a capillary tube, (2) a spherical pore with a small opening at either end, (3) a pore composed of the frustums of two right circular cones base to base, and (4) the pore space formed by the cubic packing of identical spheres.

The analysis of each of these pore spaces and the results obtained are presented in detail below.

The symbols used throughout this analysis are:

$R, r, r_0$ , radii of the pores at various cross sections,

$R_v$ , radius of the non-conducting bubble,

$R_{ss}$ , resistance of a single pore,

$A$ , area of the rectangular parallelepiped enclosing the pore at right angles to the direction of flow,

$L$ , length of the rectangular parallelepiped enclosing the pore parallel to the direction of flow,

$\rho$  resistivity,

$\rho_c$  conducting fluid resistivity,

$S_c$  conducting fluid fractional saturation,

$S_n$  non-conducting fluid fractional saturation,

$a, a', R, g, k, \phi, G$ , geometric parameters of the various pores.

1. The first part of the report is devoted to a general description of the project and its objectives.

2. The second part of the report describes the methodology used in the study.

3. The third part of the report presents the results of the study.

4. The fourth part of the report discusses the conclusions of the study.

5. The fifth part of the report contains the references.

6. The sixth part of the report contains the appendix.

7. The seventh part of the report contains the summary.

8. The eighth part of the report contains the conclusion.

9. The ninth part of the report contains the acknowledgments.

10. The tenth part of the report contains the list of figures.

11. The eleventh part of the report contains the list of tables.

12. The twelfth part of the report contains the list of abbreviations.

13. The thirteenth part of the report contains the list of symbols.

14. The fourteenth part of the report contains the list of units.

15. The fifteenth part of the report contains the list of equations.

16. The sixteenth part of the report contains the list of formulas.

17. The seventeenth part of the report contains the list of diagrams.

18. The eighteenth part of the report contains the list of graphs.

19. The nineteenth part of the report contains the list of charts.

20. The twentieth part of the report contains the list of maps.

21. The twenty-first part of the report contains the list of photographs.

22. The twenty-second part of the report contains the list of drawings.

23. The twenty-third part of the report contains the list of illustrations.

24. The twenty-fourth part of the report contains the list of figures.

25. The twenty-fifth part of the report contains the list of tables.

### Capillary Tube

Consider a capillary tube of dimensions as given by Figure I-1. The resistance of such a pore filled with a brine of resistivity  $\rho_w$  may be written directly.

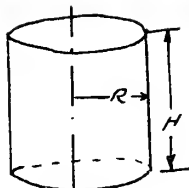


Figure I-1

$$Res_o = \rho_w \frac{H}{\pi R^2} \quad (1)$$

$$A = 4R^2 \quad L = H$$

$$\rho_o = Res_o \left( \frac{A}{L} \right) = \rho_w \left( \frac{H}{\pi R^2} \right) \left( \frac{4R^2}{H} \right) = \frac{4\rho_w}{\pi} \quad (2)$$

In the case of partial saturation if the non-conducting fluid takes the form of a cylinder concentric with, and within the pore, the partially saturated pore takes the configuration given by Figure I-2.

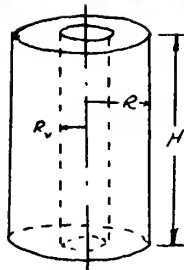


Figure I-2

Assuming that a negligible amount of current flows through the non-conducting fluid, the resistance is:

$$Res_i = \rho_w \frac{H}{\pi(R^2 - R_v^2)} \quad (3)$$

# Problem 1

Let  $V$  be the volume of the solid obtained by revolving the region bounded by the curve  $y = \sqrt{1-x^2}$  and the  $x$ -axis about the  $y$ -axis. Find  $V$ .

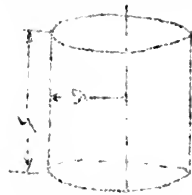


Figure 1

(1)

$$V = \pi r^2 h = \pi (1)^2 (2) = 2\pi$$

$$V = 2\pi$$

(2)

$$V = \pi \int_{-1}^1 (1-x^2)^2 dx = \pi \int_{-1}^1 (1-2x^2+x^4) dx = \pi \left[ x - \frac{2}{3}x^3 + \frac{1}{5}x^5 \right]_{-1}^1 = \pi \left( 1 - \frac{2}{3} + \frac{1}{5} - \left( -1 + \frac{2}{3} - \frac{1}{5} \right) \right) = \pi \left( 1 - \frac{2}{3} + \frac{1}{5} + 1 - \frac{2}{3} + \frac{1}{5} \right) = \pi \left( 2 - \frac{4}{3} + \frac{2}{5} \right) = \pi \left( \frac{10}{5} - \frac{4}{3} + \frac{2}{5} \right) = \pi \left( \frac{10}{5} + \frac{2}{5} - \frac{4}{3} \right) = \pi \left( \frac{12}{5} - \frac{4}{3} \right) = \pi \left( \frac{36}{15} - \frac{20}{15} \right) = \pi \left( \frac{16}{15} \right) = \frac{16\pi}{15}$$

Let  $V$  be the volume of the solid obtained by revolving the region bounded by the curve  $y = \sqrt{1-x^2}$  and the  $x$ -axis about the  $x$ -axis. Find  $V$ .



Figure 2

Let  $V$  be the volume of the solid obtained by revolving the region bounded by the curve  $y = \sqrt{1-x^2}$  and the  $x$ -axis about the  $x$ -axis. Find  $V$ .

$$V = \pi \int_{-1}^1 (1-x^2)^2 dx = \pi \int_{-1}^1 (1-2x^2+x^4) dx = \pi \left[ x - \frac{2}{3}x^3 + \frac{1}{5}x^5 \right]_{-1}^1 = \pi \left( 1 - \frac{2}{3} + \frac{1}{5} - \left( -1 + \frac{2}{3} - \frac{1}{5} \right) \right) = \pi \left( 1 - \frac{2}{3} + \frac{1}{5} + 1 - \frac{2}{3} + \frac{1}{5} \right) = \pi \left( 2 - \frac{4}{3} + \frac{2}{5} \right) = \pi \left( \frac{10}{5} - \frac{4}{3} + \frac{2}{5} \right) = \pi \left( \frac{10}{5} + \frac{2}{5} - \frac{4}{3} \right) = \pi \left( \frac{12}{5} - \frac{4}{3} \right) = \pi \left( \frac{36}{15} - \frac{20}{15} \right) = \pi \left( \frac{16}{15} \right) = \frac{16\pi}{15}$$

The fractional saturation of the non-conducting fluid may be written:

$$S_n = \frac{\pi R_v^2 H}{\pi R^2 H} = \left(\frac{R_v}{R}\right)^2$$

And

$$R_v = R S_n^{1/2} \quad (4)$$

Combining (3) and (4)

$$R_{es_i} = \rho_w \frac{H}{\pi R^2 (1 - S_n)} = \frac{\rho_w H}{\pi R^2 S_i} \quad (5)$$

Then

$$\rho_i = R_{es_i} \left(\frac{A}{L}\right) = \frac{4 \rho_w H}{\pi S_i} \quad (6)$$

From (2) and (6) the relationship for the relative resistivity may be written:

$$\frac{\rho_o}{\rho_i} = \frac{\frac{4 \rho_w}{\pi}}{\frac{4 \rho_w}{\pi S_i}} = S_i \quad (7)$$

Or in the capillary tube pore the resistivity varies linearly with the conducting fluid saturation.

### Spherical Pore

The spherical pore studied is shown by Figure I-3. The initial condition is that where the pore is completely filled with brine.

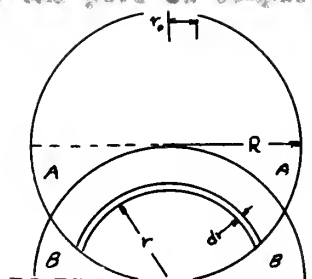


Figure I-3

The following are the results of the experiment:

For all cases:

$$\frac{Z_1}{Z_2} = \frac{H_1}{H_2} = \left(\frac{R_1}{R_2}\right)^2$$

and

$$Z_1 - Z_2 = \frac{H_1}{H_2} - \frac{H_2}{H_1}$$

(a)

For all cases:

$$\frac{H_1}{H_2} = \frac{Z_1}{Z_2} = \left(\frac{R_1}{R_2}\right)^2$$

(b)

and

$$\frac{H_1}{H_2} = \frac{Z_1}{Z_2} = \left(\frac{R_1}{R_2}\right)^2$$

(c)

The following are the results of the experiment:

For all cases:

$$\frac{H_1}{H_2} = \frac{Z_1}{Z_2} = \left(\frac{R_1}{R_2}\right)^2$$

(d)

The following are the results of the experiment:

For all cases:



In determining the resistance of the spherical pore the resistances of incremental spherical shells, varying in radius from  $r_0$  to  $R$ , and of thickness  $dr$ , are summed up. Since the solid angle of integration will be from 0 to  $\pi$  radians (ie, for hemispheres), the addition of resistances B will be compensated by the omission of resistances A.

$$Res_o = 2\rho_w \int_{r_0}^R \frac{dr}{2\pi r^2} = \frac{\rho_w}{\pi} \left( \frac{1}{r_0} - \frac{1}{R} \right) \quad (8)$$

$$\rho_o = Res_o \left( \frac{A}{L} \right) = \frac{\rho_w}{\pi} \left( \frac{1}{r_0} - \frac{1}{R} \right) \left( \frac{4R^2}{2R} \right) = \frac{2\rho_w R}{\pi} \left( \frac{1}{r_0} - \frac{1}{R} \right) \quad (9)$$

$$\text{For } r_0 = \frac{R}{c}$$

$$\rho_o = \left( \frac{2\rho_w}{\pi} \right) (c-1)$$

For partial saturation consider a spherical bubble of non-conducting fluid of radius  $R_f$  at the center of the pore. (Figure I-4). A somewhat different analysis must be used for this condition. In the region  $r_0 < r < R_f$  the spherical shells used for the completely saturated pore are again a valid approach to the summation of resistivities. In the region  $R_f < r < R$  flat washerlike discs are used because here they are representative of the flow pattern.

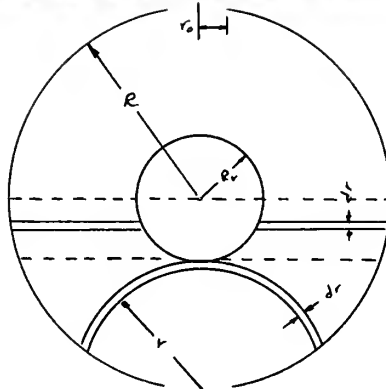


Figure I-4

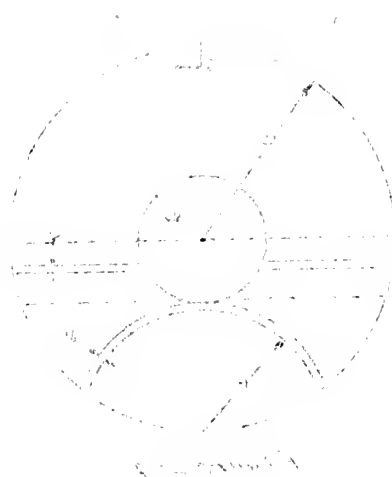
1. The first part of the problem is to find the area of the region bounded by the curve  $y = \sqrt{1-x^2}$  and the line  $y = x$  in the first quadrant. The curve is a quarter-circle of radius 1, and the line is a straight line from the origin to (1,1). The region is shaded in the diagram.

$$(1) \quad \left( \frac{1}{2} - \frac{1}{2} \right) \frac{\pi}{4} = \frac{\pi}{8} \quad \text{Area} = \frac{\pi}{8}$$

$$(2) \quad \left( \frac{1}{2} - \frac{1}{2} \right) \frac{\pi}{4} = \left( \frac{1}{2} - \frac{1}{2} \right) \frac{\pi}{4} = \left( \frac{1}{2} - \frac{1}{2} \right) \frac{\pi}{4} = \frac{\pi}{8} \quad \text{Area} = \frac{\pi}{8}$$

$$\frac{\pi}{8} = \frac{\pi}{8}$$

$$\left( \frac{1}{2} - \frac{1}{2} \right) \frac{\pi}{4} = \frac{\pi}{8}$$





Thus the resistance at any partial saturation,  $s < 1$ , becomes:

$$\begin{aligned} Res_i &= 2P_w \int_0^{R \cdot R_v} \frac{dr}{2\pi r^2} + 2P_w \int_{R \cdot R_v}^R \frac{dr}{\pi(R^2 - R_v^2)} \\ &= \frac{P_w}{\pi} \left[ \left( \frac{1}{r_0} - \frac{1}{R \cdot R_v} \right) + \left( \frac{2R_v}{R^2 - R_v^2} \right) \right] \end{aligned} \quad (11)$$

From which:

$$P_i = \frac{2P_w R}{\pi} \left[ \left( \frac{1}{r_0} - \frac{1}{R \cdot R_v} \right) + \left( \frac{2R_v}{R^2 - R_v^2} \right) \right] \quad (12)$$

$$\text{For } r_0 = \frac{R}{c}$$

$$P_i = \frac{2P_w R}{\pi} \left[ \left( \frac{c}{R} - \frac{1}{R \cdot R_v} \right) + \left( \frac{2R_v}{R^2 - R_v^2} \right) \right] \quad (13)$$

As before:

$$S_n = \frac{\frac{4}{3}\pi R_v^3}{\frac{4}{3}\pi R^3} = \left( \frac{R_v}{R} \right)^3$$

And

$$R_v = R S_n^{1/3}$$

From (13)

$$P_i = \frac{2P_w}{\pi} \left[ c - \frac{1}{1 - S_n^{1/3}} + \frac{2S_n^{1/3}}{1 - S_n^{2/3}} \right] \quad (14)$$

Then the relative resistivity becomes:

$$\begin{aligned} \frac{P_o}{P_i} &= \frac{\frac{2P_w}{\pi} (c-1)}{\frac{2P_w}{\pi} \left[ c - \frac{1}{1 - S_n^{1/3}} + \frac{2S_n^{1/3}}{1 - S_n^{2/3}} \right]} \\ &= 1 - \frac{c(S_n + S_n^{1/3})}{c(1 - S_n^{2/3}) + (S_n - S_n^{2/3} + S_n^{1/3} - 1)} \end{aligned} \quad (15)$$

Writing (15) more generally

$$\frac{P_o}{P_i} = \varphi(c, s) \quad (16)$$

$$(i) \quad \lim_{x \rightarrow 0} \frac{1 - \cos x}{x^2} = \frac{0}{0} \text{ form}$$

$$\lim_{x \rightarrow 0} \frac{1 - \cos x}{x^2} = \frac{0}{0} \text{ form}$$

$$(ii) \quad \lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$(iii) \quad \lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$(iv) \quad \lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$\lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$\lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$\lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$(v) \quad \lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$\lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$\lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$(vi) \quad \lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

$$\lim_{x \rightarrow 0} \left( \frac{1}{x^2} - \frac{1}{x} \right) = \frac{0}{0} \text{ form}$$

### Conical Pore

Consider a conical pore consisting of two right circular cones base to base. (Figure I-5). In summing up the resistances in such a pore the differential element considered is a spherical cap of thickness  $dr$ .

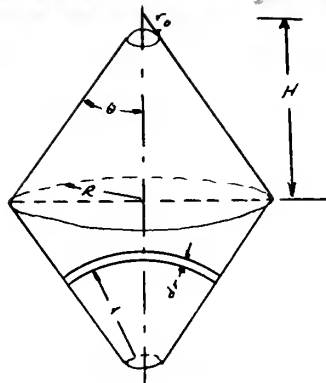


Figure I-5

The resistance of the brine filled pore is given by:

$$\begin{aligned} Res_0 &= 2P_w \int_{r_0}^H \frac{dr}{4\pi r^2 \sin^2 \frac{\theta}{2}} \\ &= \frac{P_w}{2\pi \sin^2 \frac{\theta}{2}} \left( \frac{1}{r_0} - \frac{1}{H} \right) \end{aligned} \quad (17)$$

Let  $r_0 = \frac{R}{c}$ ;  $H = \frac{R}{c'}$

Then:

$$P_0 = Res_0 \left( \frac{A}{L} \right) = Res_0 \left( \frac{4R^2}{2H} \right) = Res_0 (2c'R)$$

And

$$P_0 = \frac{c'P_w}{\pi \sin^2 \frac{\theta}{2}} (c - c') \quad (18)$$

For a condition of partial saturation a spherical bubble of radius  $A$  exists in the center of the pore, and the same treatment as for the partially saturated spherical pore may be used.



Handwritten text, possibly a title or a label, located below the diagram.

Handwritten text, possibly a description or a note, located below the first line of text.

Handwritten text, possibly a description or a note, located below the second line of text.

Handwritten text, possibly a description or a note, located below the third line of text.

Handwritten text, possibly a description or a note, located below the fourth line of text.

In the region  $r_0 < r < H - R_v$  elements consisting of spherical caps are used; in the region  $H - R_v < r < H$  washer shaped differential elements are used as before. (Figure I-6).

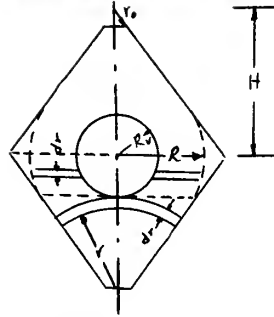


Figure I-6

Further, in the region  $H - R_v < r < H$  there will be little electrical flow in the sharp corners where the bases join, and hence a spherical outline, indicated by the dotted line Figure I-6, of radius  $R$  is used.

Then:

$$\begin{aligned} Res_i &= 2\rho_w \int_{r_0}^{H-R_v} \frac{dr}{4\pi r^2 \sin^2 \frac{\theta}{2}} + 2\rho_w \int_{H-R_v}^H \frac{dr}{\pi(R^2 - R_v^2)} \\ &= \frac{\rho_w}{2\pi \sin^2 \frac{\theta}{2}} \left( \frac{1}{r_0} - \frac{1}{H-R_v} \right) + \frac{2\rho_w}{\pi} \left( \frac{R_v}{R^2 - R_v^2} \right) \end{aligned} \quad (19)$$

$$f_i = \frac{\rho_w c'}{\pi \sin^2 \frac{\theta}{2}} \left[ (R) \left( \frac{1}{r_0} - \frac{1}{H-R_v} \right) \right] + \frac{4\rho_w c'}{\pi} \left[ (R) \left( \frac{R_v}{R^2 - R_v^2} \right) \right] \quad (20)$$

Let  $r_0 = \frac{R}{c}$ ;  $H = \frac{R}{c'}$

As in the previous cases

$$S_n = \frac{\frac{4}{3}\pi R_v^3}{\frac{2}{3}\pi R^3 \left( \frac{c^2 + c + 1}{c^2 c^2} \right)} = \frac{2R_v^3}{R^3 g}$$

where  $g = \frac{c^2 + c + 1}{c^2 c^2}$

And  $R_v = S_n^{1/3} \left( \frac{g}{2} \right)^{1/3} R = R_k S_n^{1/3}$

where  $k = \left( \frac{g}{2} \right)^{1/3}$

$$f(x) = \frac{1}{x^2} = x^{-2}$$

$$f'(x) = -2x^{-3}$$

$$= -\frac{2}{x^3} = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3} = -\frac{2}{x^3}$$



$$f'(x) = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$f(x) = \frac{1}{x^2} = x^{-2}$$

$$f'(x) = -2x^{-3}$$

$$= -\frac{2}{x^3} = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3} = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3} = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3} = -\frac{2}{x^3}$$

$$f'(x) = -\frac{2}{x^3}$$

rewriting equation (2)

$$P_i = \frac{\rho_w c'}{\pi \sin^2 \frac{\theta}{2}} \left[ \frac{c - c'}{1 - S_n^{1/3} c' k} \right] + \frac{4 \rho_w c'}{\pi} \left[ \frac{S_n^{1/3} k}{1 - S_n^{1/3} k^2} \right] \quad (21)$$

Then the relative resistivity becomes:

$$\begin{aligned} \frac{P_o}{P_i} &= \frac{\frac{\rho_w c'}{\pi \sin^2 \frac{\theta}{2}} (c - c')}{\frac{\rho_w c'}{\pi \sin^2 \frac{\theta}{2}} \left( c - \frac{c'}{1 - S_n^{1/3} c' k} \right) + \frac{4 c' \rho_w}{\pi} \left( \frac{S_n^{1/3} k}{1 - S_n^{1/3} k^2} \right)} \\ &= \frac{1}{1 + \frac{S_n^{1/3} k}{c - c'} \left( \frac{c'^2}{1 - S_n^{1/3} c' k} + \frac{4 \sin^2 \frac{\theta}{2}}{1 - S_n^{1/3} k^2} \right)} \quad (22) \end{aligned}$$

Since  $q$ ,  $c'$ ,  $k$  and  $\theta$ , are all functions of the geometry of the pore they may be lumped to obtain in  $G$  is a single parameter  $G$ . Doing this a generalised relation for the relative resistivity may be written. As before this relation also shows that the resistivity is dependent upon the saturation and the no electrical conduction. Thus the relative resistivity, is:

$$\frac{P_o}{P_i} = \varphi(G, S) \quad (23)$$

### Basic Problem of Uniform Squares

The pores spaces formed by the solid grains of uniform squares are regular, but somewhat more accurate than those previously discussed, resembling a cross section of a regular array of rods. Because the





density of the electrical flow field is distributed regularly, the resistances may be summed up, in the case of the completely brine filled pore, in terms of flat discs of radius  $r$  and thickness  $dr$ . For the partially saturated core in the region of the non-conducting bubble, washer shaped elements must be used. Figures I-7 and I-8 represent such a pore in a fully and partially saturated condition respectively.

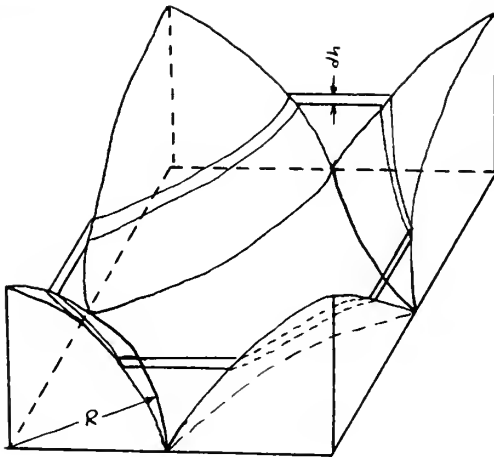


Figure I-7

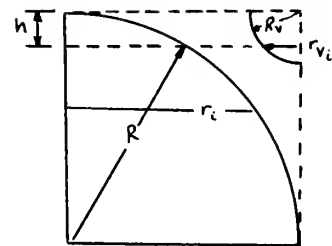


Figure I-8

The area of the opening at the entrance to the pore is:

$$a_e = 4R^2 - \pi R^2 = R^2(4 - \pi)$$

The area at the center of the pore is:

$$a_c = 4R^2$$

and any intermediate area may be written:

$$a_i = R^2(4 - \pi) + \pi h^2$$

Then the resistance of a single pore is:

$$\begin{aligned} Res_o &= 2P_w \int_0^R \frac{dh}{(4 - \pi)R^2 + \pi h^2} \\ &= \frac{2P_w}{\pi R \sqrt{\frac{4}{\pi} - 1}} \tan^{-1} \frac{1}{\sqrt{\frac{4}{\pi} - 1}} \end{aligned} \quad (24)$$



Let  $\mathbf{u}$  and  $\mathbf{v}$  be vectors in  $\mathbb{R}^3$ .

$$\mathbf{u} = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}, \quad \mathbf{v} = \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix}$$

$$\mathbf{u} \cdot \mathbf{v} = 1 \cdot 4 + 2 \cdot 5 + 3 \cdot 6 = 32$$

$$|\mathbf{u}| = \sqrt{1^2 + 2^2 + 3^2} = \sqrt{14}$$

$$|\mathbf{v}| = \sqrt{4^2 + 5^2 + 6^2} = \sqrt{77}$$

From which:

$$P = \left( \frac{2P_w}{\pi} \right) \left( \frac{1}{\sqrt{\frac{y}{n}-1}} \tan^{-1} \frac{1}{\sqrt{\frac{y}{n}-1}} \right) \quad (25)$$

For the condition of partial saturation, the area available to flow in the region of the non-conducting bubble depends upon the size of the bubble, and may be written:

$$A_v = 4R^2 - \pi [2Rh - 2h^2 + R_v^2]$$

The area available to flow outside this region is:

$$A_i = 4R^2 - 2\pi Rh + \pi h^2$$

Then the resistance of the partially saturated core becomes:

$$\begin{aligned} Res_i &= 2P_w \int_0^{R_v} \frac{dh}{4R^2 - \pi R^2 - 2\pi Rh + 2\pi h^2} + 2P_w \int_{R_v}^R \frac{dh}{4R^2 - 2\pi Rh + \pi h^2} \\ &= \frac{2P_w}{\pi} \left\{ \frac{1}{\sqrt{R^2(\frac{y}{n}-1) - 2R_v^2}} \left[ \tan^{-1} \frac{2R_v - R}{\sqrt{R^2(\frac{y}{n}-1) - 2R_v^2}} + \tan^{-1} \frac{R}{\sqrt{R^2(\frac{y}{n}-1) - 2R_v^2}} \right] \right\} \\ &\quad + \frac{2P_w}{\pi R} \left\{ \frac{1}{\sqrt{\frac{y}{n}-1}} \tan^{-1} \frac{R - R_v}{R\sqrt{\frac{y}{n}-1}} \right\} \quad (26) \end{aligned}$$

Evaluating  $R_v$  in terms of  $R$  and  $\sigma$

$$R_v = R \left[ S_n \left( \frac{y}{n} - 1 \right) \right]^{1/3}$$

Let  $\left[ S_n \left( \frac{y}{n} - 1 \right) \right]^{1/3} = \sigma$

Then equation (26) becomes:

$$\begin{aligned} Res_i &= \frac{2P_w}{\pi R} \left\{ \frac{1}{\sqrt{\frac{y}{n}-1-2\sigma^2}} \left[ \tan^{-1} \frac{2\sigma-1}{\sqrt{\frac{y}{n}-1-2\sigma^2}} + \tan^{-1} \frac{1}{\sqrt{\frac{y}{n}-1-2\sigma^2}} \right] \right. \\ &\quad \left. + \frac{1}{\sqrt{\frac{y}{n}-1}} \tan^{-1} \frac{1-\sigma}{\sqrt{\frac{y}{n}-1}} \right\} \quad (27) \end{aligned}$$

(7.8)

$$\left( \frac{1}{1 - \frac{1}{2}} \right) \left( \frac{1}{1 - \frac{1}{2}} \right) \left( \frac{1}{1 - \frac{1}{2}} \right) = \frac{1}{1 - \frac{1}{2}}$$

$$[1.9 + 1.5 + 1.5] \times 1.5 = 1.5$$

$$1.5 = 1.5 + 1.5 + 1.5 = 1.5$$

$$\frac{1}{1 - \frac{1}{2}} = \frac{1}{1 - \frac{1}{2}} = \frac{1}{1 - \frac{1}{2}}$$

$$\left\{ \frac{1}{1 - \frac{1}{2}} \right\} = \frac{1}{1 - \frac{1}{2}} = \frac{1}{1 - \frac{1}{2}}$$

$$\left\{ \frac{1}{1 - \frac{1}{2}} \right\} = \frac{1}{1 - \frac{1}{2}} = \frac{1}{1 - \frac{1}{2}}$$

$$\left[ \left( 1 - \frac{1}{2} \right) \right] = \frac{1}{1 - \frac{1}{2}}$$

$$= \frac{1}{1 - \frac{1}{2}}$$

$$\frac{1}{1 - \frac{1}{2}} = \frac{1}{1 - \frac{1}{2}} = \frac{1}{1 - \frac{1}{2}}$$

$$\left\{ \frac{1}{1 - \frac{1}{2}} \right\} = \frac{1}{1 - \frac{1}{2}} = \frac{1}{1 - \frac{1}{2}}$$

From which:

$$\rho_i = \frac{4\rho_o}{\pi} \left\{ \frac{1}{\sqrt{\frac{8}{\pi}-1-2\sigma^2}} \tan^{-1} \frac{\sigma\sqrt{\frac{8}{\pi}-1-2\sigma^2}}{\frac{4}{\pi}-\sigma^2-\sigma} + \frac{1}{\sqrt{\frac{4}{\pi}-1}} \tan^{-1} \frac{1-\sigma}{\sqrt{\frac{4}{\pi}-1}} \right\} \quad (28)$$

Then the relative resistivity becomes:

$$\frac{\rho_o}{\rho_i} = \frac{\frac{1}{\sqrt{\frac{8}{\pi}-1}} \tan^{-1} \frac{1}{\sqrt{\frac{8}{\pi}-1}}}{\frac{1}{\sqrt{\frac{8}{\pi}-1-2\sigma^2}} \tan^{-1} \frac{\sigma\sqrt{\frac{8}{\pi}-1-2\sigma^2}}{\frac{4}{\pi}-\sigma^2-\sigma} + \frac{1}{\sqrt{\frac{4}{\pi}-1}} \tan^{-1} \frac{1-\sigma}{\sqrt{\frac{4}{\pi}-1}}} \quad (29)$$

Or writing (29) more generally

$$\frac{\rho_o}{\rho_i} = \varphi(G, S) \quad (30)$$

From the development given above it may be seen that although the relative resistivity will in general take the form

$$\frac{\rho_o}{\rho_i} = \varphi(G, S)$$

there is no simple precise relationship between saturation and resistivity. As the system begins to approach a natural system, in the cubic packing of spheres, the relationship becomes very formidable indeed.

For this reason the problem was studied in terms of a additional parameter, that of the variation of hydraulic permeability with saturation.



If the equations for  $\frac{\rho_o}{\rho_c}$  are examined in the region where  $S_n$  is small, the following approximate relations may be arrived at by neglecting the higher powers of  $S_n$ .

For the spherical pore:

$$\frac{\rho_o}{\rho_c} \approx 1 - S_n^{1/3} \quad (31)$$

For the conical pore:

$$\frac{\rho_o}{\rho_c} \approx 1 - \frac{S_n}{2}^{1/3} \quad (32)$$

For the pore formed by the cubic packing of uniform spheres:

$$\frac{\rho_o}{\rho_c} \approx 1 - 1.1 S_n^{1/3} \quad (33)$$

To establish the significance of the higher order terms in these relationships, equation (29) was plotted on logarithmic coordinates along with equation (33). The experimental data of Figure 1. is also shown for comparison purposes. It may be seen immediately that the higher order terms are significant all the way and such a simplification is a poor approximation.

It should be noted, however, that the line of the experimental data is somewhat an average of these two curves. This is not surprising when one considers that the ideal pore shapes were studied as single pores, while in a randomly packed porous medium many of the individual effects will cancel each other.

Since such an averaging process will effect the electrical conductivity and hydraulic permeability similarly a relationship between the two would tend to cancel out the random effects and make the problem soluble.





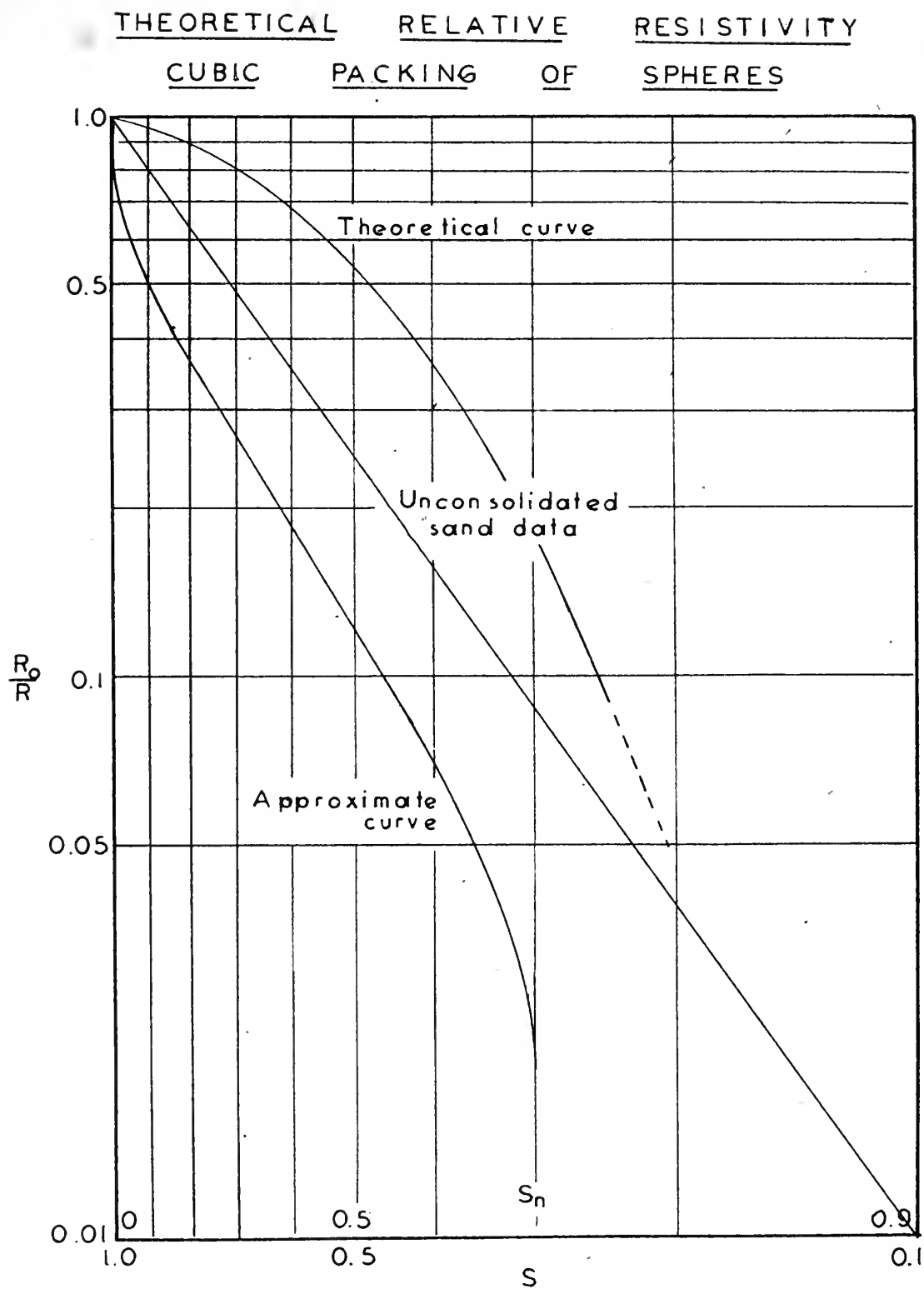


FIGURE 9.



## Conclusions

From this analysis it may be concluded:

1. The relationship between saturation and resistivity will, in general, take the form

$$\frac{\rho_o}{\rho_i} = \varphi(G, S)$$

2. For a given material, the relationship between  $\rho_o/\rho_i$  and  $S_n$  may be shown to take the form

$$\frac{\rho_o}{\rho_i} \approx 1 - c S_n^{1/3}$$

However these relationships are approximate because the higher order terms are significant at large values of  $S_n$  and  $\rho_o/\rho_i$ .

3. An additional independent parameter is required for solution of the problem.

Conclusions

1. The results of the study show that the relationship between the variables is significant. The data indicates that there is a positive correlation between the variables.

6/1/74  
(2, 3, 4, 5)

2. The study also found that the relationship between the variables is not significant. The data indicates that there is no significant correlation between the variables.

6/1/74  
(2, 3, 4, 5)

3. The study also found that the relationship between the variables is not significant. The data indicates that there is no significant correlation between the variables.

APPENDIX II

DATA

23. 23. 1941

23. 1941

# Relative Resistivity and Relative Permeability

## for Unconsolidated Sands

Table I

(Wyckoff & Botset)(11)

| <u>S</u> | <u>R<sub>o</sub>/R</u> | <u>(R<sub>o</sub>/R)<sup>2</sup></u> | <u>K<sub>w</sub>/K</u> |
|----------|------------------------|--------------------------------------|------------------------|
| 1.0      | 1.0                    | 1.0                                  | 1.0                    |
| 0.9      | 0.84                   | 0.702                                | 0.70                   |
| 0.8      | 0.67                   | 0.45                                 | 0.46                   |
| 0.7      | 0.53                   | 0.28                                 | 0.29                   |
| 0.6      | 0.39                   | 0.15                                 | 0.16                   |
| 0.5      | 0.27                   | 0.073                                | 0.08                   |
| 0.4      | 0.17                   | 0.029                                | 0.03                   |
| 0.3      | 0.09                   | 0.008                                | 0.01                   |
| 0.2      | 0.04                   | 0.0016                               | 0.005                  |

Table II

(Leverett)(14)

| <u>S</u> | <u>R<sub>o</sub>/R</u> | <u>(R<sub>o</sub>/R)<sup>2</sup></u> | <u>K<sub>w</sub>/K</u> |
|----------|------------------------|--------------------------------------|------------------------|
| 1.0      | 1.0                    | 1.0                                  | 1.0                    |
| 0.9      | 0.845                  | 0.712                                | 0.74                   |
| 0.8      | 0.69                   | 0.475                                | 0.53                   |
| 0.7      | 0.54                   | 0.29                                 | 0.36                   |
| 0.6      | 0.40                   | 0.16                                 | 0.22                   |
| 0.5      | 0.27                   | 0.073                                | 0.11                   |
| 0.4      | 0.17                   | 0.029                                | 0.05                   |
| 0.3      | 0.09                   | 0.006                                | 0.01                   |
| 0.2      | 0.04                   | 0.0016                               | -                      |

Table III

(Kogan)(15)

| <u>S</u> | <u>R<sub>o</sub>/R</u> | <u>(R<sub>o</sub>/R)<sup>2</sup></u> |
|----------|------------------------|--------------------------------------|
| 1.0      | 1.0                    | 1.0                                  |
| 0.9      | 0.81                   | 0.65                                 |
| 0.8      | 0.67                   | 0.45                                 |
| 0.7      | 0.54                   | 0.29                                 |
| 0.6      | 0.41                   | 0.17                                 |
| 0.5      | 0.29                   | 0.084                                |
| 0.4      | 0.20                   | 0.040                                |
| 0.3      | 0.12                   | 0.014                                |
| 0.2      | 0.06                   | 0.004                                |

Table IV

(Dunlap)(7)

| <u>S</u> | <u>R<sub>o</sub>/R</u> | <u>(R<sub>o</sub>/R)<sup>2</sup></u> |
|----------|------------------------|--------------------------------------|
| 1.0      | 1.0                    | 1.0                                  |
| 0.9      | 0.92                   | 0.845                                |
| 0.8      | 0.72                   | 0.52                                 |
| 0.7      | 0.54                   | 0.29                                 |
| 0.6      | 0.39                   | 0.15                                 |
| 0.5      | 0.28                   | 0.08                                 |
| 0.4      | 0.17                   | 0.029                                |
| 0.3      | 0.09                   | 0.006                                |
| 0.2      | 0.04                   | 0.002                                |

Table V

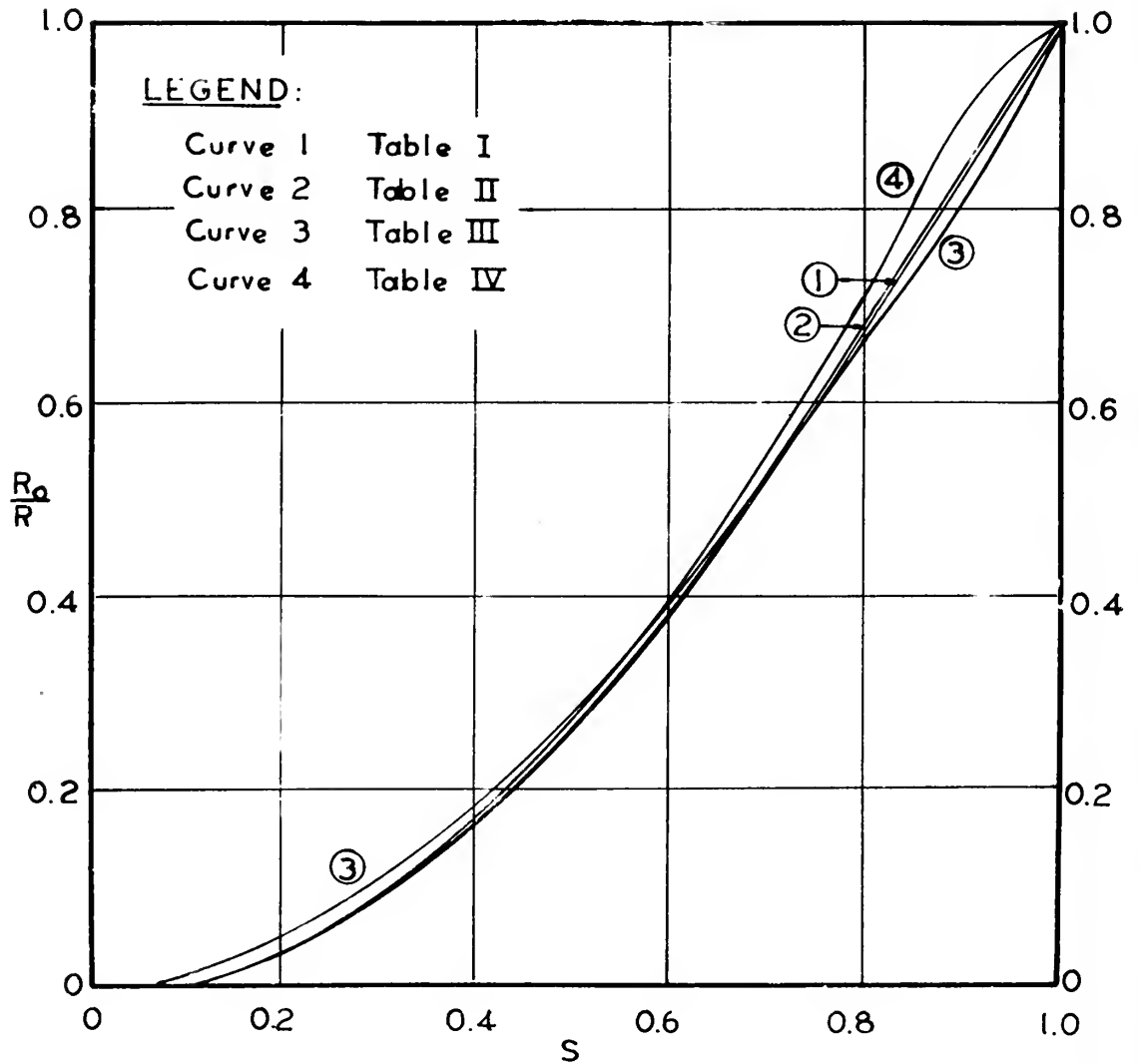
(Average)

| <u>S</u> | <u>R<sub>o</sub>/R</u> | <u>(R<sub>o</sub>/R)<sup>2</sup></u> | <u>K<sub>w</sub>/K</u> |
|----------|------------------------|--------------------------------------|------------------------|
| 1.0      | 1.0                    | 1.0                                  | 1.0                    |
| 0.9      | 0.854                  | 0.729                                | 0.72                   |
| 0.8      | 0.688                  | 0.473                                | 0.495                  |
| 0.7      | 0.538                  | 0.279                                | 0.325                  |
| 0.6      | 0.398                  | 0.158                                | 0.190                  |
| 0.5      | 0.278                  | 0.077                                | 0.095                  |
| 0.4      | 0.180                  | 0.032                                | 0.040                  |
| 0.3      | 0.098                  | 0.0096                               | 0.01                   |
| 0.2      | 0.045                  | 0.002                                | -                      |





SPREAD OF RELATIVE RESISTIVITY DATA  
FOR UNCONSOLIDATED SANDS



NOTE: The average of these curves is represented by curve 1, Figure 4.

FIGURE 8.



Relative Resistivity and Relative Permeability Data

Table VI

(Consolidated Natural Core)

(Morse)(12)

Bradford Sand, Air Permeability 93 md., Porosity 20.2%

| <u>S</u> | <u>R<sub>o</sub>/R</u> | <u>(R<sub>o</sub>/R)<sup>2</sup></u> | <u>(R<sub>o</sub>/R)<sup>1.5</sup></u> | <u>K<sub>w</sub>/K</u> |
|----------|------------------------|--------------------------------------|--|------------------------|
| 1.0      | 1.0                    | 1.0                                  | 1.0                                    | 1.0                    |
| 0.9      | 0.40                   | 0.150                                | 0.253                                  | 0.37                   |
| 0.8      | 0.25                   | 0.063                                | 0.126                                  | 0.24                   |
| 0.7      | 0.17                   | 0.029                                | 0.071                                  | 0.12                   |
| 0.6      | 0.11                   | 0.012                                | 0.037                                  | 0.05                   |
| 0.5      | 0.07                   | 0.005                                | 0.018                                  | 0.01                   |
| 0.4      | 0.05                   | 0.002                                | 0.010                                  | -                      |

Table VII

(Consolidated Synthetic Core)

(Morse)(12)

| <u>S</u> | <u>R<sub>o</sub>/R</u> | <u>(R<sub>o</sub>/R)<sup>2</sup></u> | <u>K<sub>w</sub>/K</u> |
|----------|------------------------|--------------------------------------|------------------------|
| 1.0      | 1.0                    | 1.0                                  | 1.0                    |
| 0.9      | 0.84                   | 0.71                                 | -                      |
| 0.8      | 0.73                   | 0.53                                 | 0.53                   |
| 0.7      | 0.54                   | 0.29                                 | 0.31                   |
| 0.6      | 0.42                   | 0.18                                 | 0.18                   |
| 0.5      | 0.31                   | 0.11                                 | 0.11                   |
| 0.4      | 0.20                   | 0.04                                 | 0.05                   |
| 0.3      | 0.12                   | 0.014                                | 0.015                  |



Relative Resistivity Data  
for Clean Unconsolidated Sand

Table VIII  
(Dunlap<sup>(7)</sup>, Figure 5)

| <u>Top Part of Core</u> |                        |                                       | <u>Middle Part of Core</u> |                        |                                       | <u>Bottom Part of Core</u> |                        |                                       |
|-------------------------|------------------------|---------------------------------------|----------------------------|------------------------|---------------------------------------|----------------------------|------------------------|---------------------------------------|
| <u>S</u>                | <u>R<sub>0</sub>/R</u> | <u>(R<sub>0</sub>/R)S<sup>2</sup></u> | <u>S</u>                   | <u>R<sub>0</sub>/R</u> | <u>(R<sub>0</sub>/R)S<sup>2</sup></u> | <u>S</u>                   | <u>R<sub>0</sub>/R</u> | <u>(R<sub>0</sub>/R)S<sup>2</sup></u> |
| 1.0                     | 1.0                    | 1.0                                   | 1.0                        | 1.0                    | 1.0                                   | 1.0                        | 1.0                    | 1.0                                   |
| 0.89                    | 0.917                  | 0.725                                 | 0.74                       | 0.86                   | 0.470                                 | 0.90                       | 1.0                    | 0.640                                 |
| 0.82                    | 0.735                  | 0.526                                 | 0.67                       | 0.307                  | 0.133                                 | 0.73                       | 0.833                  | 0.444                                 |
| 0.75                    | 0.550                  | 0.319                                 | 0.53                       | 0.153                  | 0.052                                 | 0.67                       | 0.833                  | 0.374                                 |
| 0.65                    | 0.306                  | 0.129                                 | 0.53                       | 0.116                  | 0.033                                 | 0.57                       | 0.714                  | 0.232                                 |
| 0.53                    | 0.153                  | 0.052                                 | 0.47                       | 0.100                  | 0.0220                                | 0.52                       | 0.312                  | 0.084                                 |
| 0.54                    | 0.121                  | 0.035                                 | 0.44                       | 0.092                  | 0.0178                                | 0.50                       | 0.278                  | 0.0695                                |
| 0.49                    | 0.112                  | 0.027                                 | 0.42                       | 0.075                  | 0.0132                                | 0.45                       | 0.212                  | 0.0428                                |
| 0.45                    | 0.106                  | 0.021                                 | 0.36                       | 0.070                  | 0.0091                                | 0.42                       | 0.200                  | 0.0353                                |
| 0.43                    | 0.097                  | 0.013                                 | 0.32                       | 0.063                  | 0.0065                                | 0.37                       | 0.143                  | 0.0196                                |
| 0.37                    | 0.037                  | 0.012                                 | 0.30                       | 0.061                  | 0.0055                                | 0.32                       | 0.125                  | 0.0123                                |
| 0.33                    | 0.078                  | 0.0035                                | 0.29                       | 0.061                  | 0.0051                                | 0.27                       | 0.100                  | 0.0073                                |
| 0.30                    | 0.078                  | 0.0070                                | 0.27                       | 0.061                  | 0.0044                                | 0.25                       | 0.077                  | 0.0043                                |
| 0.27                    | 0.073                  | 0.0056                                | 0.24                       | 0.054                  | 0.0031                                | 0.24                       | 0.062                  | 0.0036                                |
| 0.24                    | 0.073                  | 0.0042                                | 0.23                       | 0.043                  | 0.0025                                | 0.22                       | 0.049                  | 0.00216                               |
| 0.23                    | 0.061                  | 0.0032                                | 0.21                       | 0.041                  | 0.00130                               | 0.20                       | 0.043                  | 0.00172                               |
| 0.22                    | 0.054                  | 0.0026                                | 0.20                       | 0.037                  | 0.00143                               | 0.19                       | 0.041                  | 0.00148                               |
| 0.21                    | 0.050                  | 0.00220                               | 0.13                       | 0.029                  | 0.00094                               | 0.17                       | 0.031                  | 0.00090                               |
| 0.19                    | 0.043                  | 0.00173                               | 0.17                       | 0.025                  | 0.00072                               | 0.15                       | 0.020                  | 0.00045                               |
| 0.13                    | 0.042                  | 0.00136                               | 0.15                       | 0.018                  | 0.00040                               | 0.14                       | 0.019                  | 0.00037                               |
| 0.17                    | 0.032                  | 0.00092                               | 0.13                       | 0.014                  | 0.00024                               | 0.13                       | 0.014                  | 0.00024                               |



Relative Permeability Data for Unconsolidated Sands

Table IX

(Wyckoff & Botset)(11)

| <u>S</u> | <u>K<sub>w</sub>/K</u> |
|----------|------------------------|
| 1.0      | 1.0                    |
| 0.9      | 0.70                   |
| 0.8      | 0.46                   |
| 0.7      | 0.29                   |
| 0.6      | 0.16                   |
| 0.5      | 0.08                   |
| 0.4      | 0.035                  |
| 0.3      | 0.010                  |
| 0.2      | 0.005                  |

Relative Resistivity and Relative Permeability Data  
for a Consolidated Sand

Table X

(Morse)(12)

Bradford Sand, Air Permeability 93 md., Porosity 20.2%

| <u>S</u> | <u>R<sub>0</sub>/R</u> | <u>(R<sub>0</sub>/R)S<sup>2</sup></u> | <u>K<sub>w</sub>/K</u> |
|----------|------------------------|---------------------------------------|------------------------|
| 1.0      | 1.0                    | 1.0                                   | 1.0                    |
| 0.9      | 0.40                   | 0.324                                 | 0.37                   |
| 0.8      | 0.25                   | 0.160                                 | 0.24                   |
| 0.7      | 0.17                   | 0.083                                 | 0.12                   |
| 0.6      | 0.11                   | 0.0396                                | 0.04                   |
| 0.5      | 0.07                   | 0.0175                                | 0.01                   |
| 0.4      | 0.05                   | 0.0030                                | -                      |





### APPENDIX III

DEFINITION OF "RELATIVE RESISTIVITY"

THE HISTORY

OF THE UNITED STATES OF AMERICA

### Definition of "Relative Resistivity"

Relative resistivity as used throughout this work is actually the Relative reciprocal resistivity, or the relative conductivity. However for clarity and brevity, the term relative resistivity is used.

It should be noted that relative reciprocal resistivity, or relative conductivity, is the electrical analog of relative permeability and varies between 1.0 and 0.0. Relative resistivity on the other hand varies between 1.0 and infinity. It is the former term, with appropriate limits, which is used throughout this work.

Definition of Terms

1. Definition of Terms

2. Definition of Terms

3. Definition of Terms

4. Definition of Terms

5. Definition of Terms

6. Definition of Terms

7. Definition of Terms

8. Definition of Terms

S. A. V. 2. N

P8

W.S.V.A. F.  
89









## DATE DUE

[illegible]

Thesis  
R32 Reh

13060

Theoretical investigations of the resistivity-saturation relationship in porous material.

Thesis  
R32 Reh

13060

Theoretical investigations of the resistivity-saturation relationship in porous material.

thesR32

Theoretical investigations of the resist



3 2768 001 01306 3

DUDLEY KNOX LIBRARY